5A
2nd set.

THE UNIVERSITY OF NEW SOUTH WALES

water research laboratory

Manly Vale, N.S.W., Australia

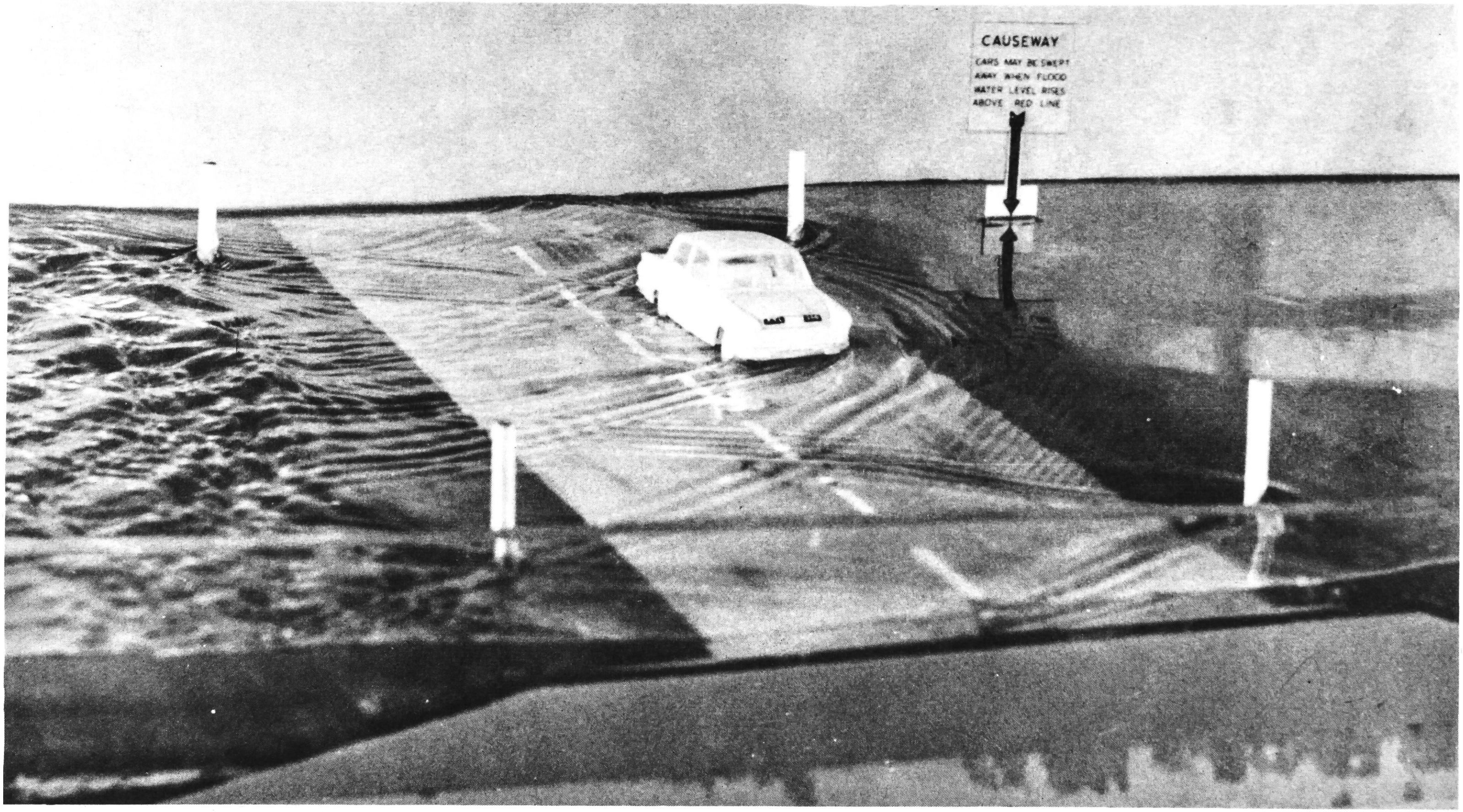
Report No. 100

LOW LEVEL CAUSEWAYS

by

A. J. Bonham and R. T. Hattersley

August, 1967



1. Model of recommended causeway with downstream crossfall.

The University of New South Wales

WATER RESEARCH LABORATORY

LOW LEVEL CAUSEWAYS

by

A. J. Bonham and R. T. Hattersley

Report No. 100

August, 1967.

----

https://doi.org/10.4225/53/579835d2ef671

Preface

Arising from discussions with Engineers of the Department of Public Works, work was undertaken by the Water Research Laboratory to study the hydraulics of flow over low level causeways.

Causeways of this kind are common in New South Wales. They are provided at stream crossings where finance for bridge construction is not available. However, causeways are typically built with a piped length to carry the long period, dry weather flow.

The questions for which answers were sought related to the extent of dry crossing waterway area to be allowed, the best pavement cross section for hydraulic purposes and the possible effects of wave motion and scour.

Before investigations had proceeded far it was found that matters already mentioned were so closely related to vehicle design that all factors needed an overall study.

The hydraulic investigations included model studies in a flume to determine lift and drag effects of flood flow on a vehicle on a flooded crossing. Model results were analysed using data supplied by motor car manufacturers and the analysis is set out in the form of safety recommendations.

The work was carried out with the aid of a grant of funds from the Department of Public Works, New South Wales, under the direction of the Officer-in-Charge of the Water Research Laboratory.

The early investigations, which included a questionnaire survey and model tests, were carried out by Mr. B. A. Cornish, Project Engineer, under the supervision of Mr. D. N. Foster, Senior Lecturer in Civil Engineering. Mr. A. J. Bonham, Project Engineer, completed the analysis of model results, extended them to all types of cars and developed the causeway design criteria.

The assistance and advice of the Engineering Staff of the Public Works Department of N. S. W. is gratefully acknowledged as also are contributions by the Ford Motor Company, General Motors Holden, The British Motor Corporation, Volkswagen Corporation and the Olympic Tyre and Rubber Company and those Shire and Municipal Engineers who contributed to the questionnaire.

The report in its present form includes suggestions towards improvement of road safety standards but it is realised that the methods finally adopted need to be shaped by the requirements of road construction standards and authorities on road safety and traffic. These matters are beyond the scope of this laboratory. Discussion and criticism of the suggestions will therefore be welcome.

R. T. Hattersley,
Assoc. Professor of Civil Engineering,
Officer-in-Charge,
Water Research Laboratory.

September, 1967.

Summary

Tests were made with a model Falcon car and with model causeway sections to establish criteria for the safe design of submersible causeways for use on country roads.

These criteria will enable highway authorities to design safe causeways and the safe limits can be clearly defined for the motorist by means of the proposed warning indicator notices.

Table of Contents

		Page No.
1.	Introduction	1.
2.	Causeways and Case Histories in New South Wales	2.
	2.1 Definition - Causeways, Floodways and Fords	2.
	2.2 Causeway Survey	3.
	2.3 Accidents on Causeways	3.
3.	Experimental Tests with a Model Car	7.
	3.1 Test Procedure	7.
	3.2 Performance on a Floodway	7.
	3.3 Performance on a Causeway	7.
4.	Causeway Road Friction Factor	8.
	4.1 General	8.
	4.2 Value Selected	10.
5.	Hydraulic Characteristics of Cars	11.
	5.1 Car Statistics	11.
	5.2 Principle of Similarity	12.
	5.3 Class 1. Medium Sized Conventional Cars	15.
	5.4 Class 2. Small Conventional Cars	15.
	5.5 Class 3. Front Wheel Drive Cars	15.
	5.6 Class 4. Rear Engined Cars	15.
	5.7 Class 5. American Cars	16.
	5.8 Class 6. Sports Cars	16.
	5.9 Class 7. Others	16.
	5.10 Discussion - New Lightweight Cars	16.
6.	Experimental Tests with Model Causeways	17.
	6.1 Flat Causeways	17.
	6.2 Causeways with Upstream Camber	17.
	6.3 Causeways with Downstream Camber	18.
	6.4 Causeways over Culvert Pipes	18.
	6.5 Conclusion	18.
7.	Warning Indicator Notice	18.
	7.1 General	18.
	7.2 Operation of the Warning Indicator Notice	19.
	7.3 Flat Causeways	20.

Table of Contents (cont'd.)

		Page No.
	7.4 Causeways with Upstream Camber	20.
	7.5 Causeways with Downstream Camber	21.
	7.6 Causeways with Subcritical Flow and Floodways	21.
	7.7 Additional Notice for Heavy Cars	21.
	7.8 Summary	22.
8.	Causeway Design Recommendations	22.
	8.1 General Considerations	22.
	8.2 Design Details	23.
	8.3 Example	25.
9.	Conclusions	25.
	9.1 Bridges are Preferable	25.
	9.2 Causeway Accidents	26.
	9.3 Tests with Model Car	26.
	9.4 Road Friction Factor	26.
	9.5 The Motor Car	26.
	9.6 Tests with Model Causeways	26.
	9.7 Warning Indicator Notice	27.
	9.8 Design Recommendations	27.
	9.9 General Conclusion	27.
References		28.
List of Figures		
List of Tables		
List of Photographs		

List of Figures.

		Section
1.	Location map of known causeways in New South Wales	2.2
2.	Model car on elevated causeway	3.3
3.	Horizontal and vertical reactions of Falcon cars on causeways from model tests	3.3
4.	Limiting stability for Falcon cars on causeways for various values of friction between car wheels and causeway surface	3.3
5.	Limiting stability on causeways for more floatable cars for coefficient of friction $\mu = 0.3$	5.2
6.	Buoyancy in still water - Falcon	5.2
7.	Buoyancy in still water - Holden	5.2
8.	Buoyancy in still water - Volkswagen	5.2
9.	Car elevations - Ford Falcon, Chrysler Valiant, Morris Mini-van	5.6
10.	Car elevations - Toyota Corona, Hillman Hunter, Hillman Super Minx	5.6
11.	Car elevations, Ford Cortina, Vauxhall Viva, Opel Record	5.6
12.	Car elevations - Morris Mini, Morris 1100, Austin 1800	5.6
13.	Car elevations - Volkswagen, Fiat 600D, Hillman Imp	5.6
14.	Causeway flow characteristics - level surface (by Woodburn)	6.4
15.	Causeway flow characteristics - upstream camber	6.4
16.	Causeway flow characteristics - upstream camber velocity distribution	6.4
17.	Causeway flow characteristics - downstream camber slope 1 in 25	6.4
18.	Causeway flow characteristics - downstream camber velocity distribution	6.4
19.	Causeway flow characteristics - downstream camber II	6.4
20.	Causeway flow characteristics - downstream camber III (by Woodburn)	6.4
21.	Warning Indicator Notice	7.2
22.	Supplementary notice for heavy cars and vehicles	7.7
23.	Perspective sketch of proposed causeway	8.1
24.	Cross section of proposed causeway	8.1
25.	Flow duration curve, Jerrabomberra Creek at Narrabundah Lane near Canberra	8.3

List of Tables.

		Section
1.	Typical reply to the Causeway Survey Questionnaire	2.3
2.	Road friction factor	4.2
3.	Registrations of new cars in New South Wales in 1966, classified for performance on flooded causeways	5.2
4.	Total registrations of all vehicles in New South Wales, November 1966	5.2
5.	Application of results of tests with model Falcon to other cars	5.2

List of Photographs

1.	Model of recommended causeway with downstream crossfall	Frontispiece
2.	Model Falcon car under test	3.3
3.	End view of model Falcon car under test	3.3
4.	Cars passing on model of recommended causeway	8.1
5.	Model of recommended causeway with downstream camber	8.2

1. Introduction

This report covers the investigations made since 1962 to develop design standards and safety standards for causeways to apply for the wide range of motor vehicles in New South Wales.

There is a general trend in motor car design towards cars which will more easily float or be swept away by the flow of water over causeways. This results from the elimination of the separate car chassis in favour of a lower unitised body with low floor trays at the minimum acceptable road clearance level. Improved dust proofing results in watertight interiors so that a floating car may take some time to fill and sink. The improved manufacturing structural techniques enable us to enjoy longer, wider and lighter car bodies so that an increased frequency of this type of accident can be expected. Information from the various car manufacturers confirms that this trend will continue in the future.

A brief description is given of a fairly common causeway incident to illustrate the problem. The car will cautiously proceed on to the flooded causeway. The driver may not realise that an appreciable buoyancy force will be developed under the car in a small depth of water. This buoyancy will reduce the reaction between the tyres and the causeway surface, and at the same time the flow of water will produce a lateral pressure against the side of the car. The car will perhaps move forward into progressively deeper water or into a faster current until the lateral pressure against the side of the car will exceed the maximum frictional resistance which can be developed by the car tyres on the causeway surface under the reduced vertical loading. The rear wheels will slide and probably spin and the car will perhaps slew round and face upstream. The car will probably then roll backwards off the causeway into deeper water and float away downstream.

There are upwards of 2,500 such causeways on the western slopes of the great dividing range in New South Wales and many others elsewhere. These causeways and their accident history are discussed in Section 2 of this report.

Experiments were made with a model Falcon Sedan in a test flume against a wide range of water depth and velocity in order to establish the limiting range of flows for car stability. (See Section 3).

The minimum road friction factor to be adopted is examined in Section 4.

Vehicle types were examined and classified to ensure that any proposed safety measures will apply to the range of cars in use on the roads.(see Section 5.)

Experimental tests with model causeway sections are evaluated in Section 6.

A Warning Indicator Notice is proposed in Section 7 and also an additional small notice for the guidance of heavy cars.

The principles and details of the design of safe causeways to suit Australian conditions are outlined in Section 8, making use of the Warning Indicator Notice.

2. Causeways and Case Histories in New South Wales

2.1 Definition - Causeways, Floodways and Fords

The S. A. A. Glossary of Terms used in Road Engineering contains the following definitions for "causeway" and "floodway".

"Causeway": A carriageway across a watercourse or across tidal water, especially constructed to resist the effects of submergence.

"Floodway": A carriageway across a shallow depression subject to flooding, especially constructed to resist the effects of submergence.

"Ford": A shallow place in a stream where the bed may be crossed by traffic.

In this report these three types of crossing are generally dealt with together. For the present purposes a Floodway is considered to be the limiting case of a Causeway where the velocity of the floodwater across the carriageway is zero. That is to say everything which applies to a Causeway applies to a Floodway except for the effects of velocity such as lateral pressure against the side of the car or downstream scour.

Floodways tend to be less dangerous than causeways because a floating car will not be swept away into deep water except in windy conditions.

However, when the question of warning notices is considered in Section 7, causeways, floodways and fords are each given their correct description as recommended by the S. A. A. code.

2. 2 Causeway Survey

A questionnaire was sent to all Shire and Municipal Councils in New South Wales in order to assess the extent of the problem in this State. Answers were requested concerning the existence of causeways, types of causeways, design standards and accident records if any. The response to the questionnaire was limited in value by the omission of replies by many important local authorities. A typical reply is included in Table 1.

The survey showed that causeways are located in all parts of the State. The greatest number of causeways occurs in the tableland area and western slopes west of the Dividing Range, where upwards of 2,500 were reported, in an area having an average rainfall of 25 inches. Figure 1 is the location map of known causeways in New South Wales.

2. 3 Accidents on Causeways

The survey has shown that there have been many hundreds of accidents at causeways in recent times. The occurrence of accidents is so commonplace in periods of heavy rain that the news value is low and often no report is included on the radio news or in the large circulation press unless someone is drowned, or there is some other special news value. In February 1967, there were a number of cases of cars floating away, even near to Sydney, in addition to the tragic case at Oxford Falls in the Warringah Shire. Some of these incidents received no publicity.

It is estimated that deaths due to cars being swept from causeways in recent times run well into three figures in New South Wales.

Future accidents on causeways may be avoided, by careful drivers, if adequate design and operational standards are adopted as proposed in this report.

Table 1: Causeway Survey Questionnaire - SPECIMEN REPLY

Shire or Municipality of ______ BOREE ______

Design Data:

1. Number of causeways in use ______ 165 ______
2. Number of causeways at bed level of stream ______ 155 ______
3. Number built above bed level - of any design ______ 10 ______
4. Number built above bed level - with dry weather underpasses ______ 5 ______
5. Basis for waterway design usually adopted, if any ______ D.M.R. WATERWAY CALCULATIONS 1939 ______
6. Basis for design of approaches and crossings e.g. D. M. R. or other ______ D.M.R. ______

Accidents:

7. Number of known causeway accidents in 10 years or other stated period ______ APPROX. 350 IN 10 YEARS INCL. MINOR ACCIDENTS ______

*8. Number attributable to flood conditions e.g. vehicle washed off ______ 340 INCL. MINOR ACCIDENTS ______

   (i) Road level causeway ______ 335 ______

   (ii) Raised causeway ______ 5 ______

*9. Number attributable to driving errors ______ 20 ______

Note: Details of accident cases deemed worthy of further study may be noted on attached sheet

* If accident causes in (8)(i), 8(ii) and (9) are considered contributory count the accidents under each heading

Stream History:

10. Number of causeways to which are attributable

   (i) Stream siltation ______ 20 ______

   (ii) Erosion of bed ______ 55 ______

   (iii) Erosion of banks ______ 30 ______

Table 1: (cont'd.)

11. Approx. frequency of flooding of causeway with worst accident record

    (i) With causeway passable — FOUR TIMES YEARLY

    (ii) With causeway impassable — TWICE YEARLY

12. Normal traffic density vehicles per day — 20 TO 120

13. Particulars of any causeway site deemed worthy of investigation as part of a general study of causeway design. See attachment — M. R. 238 6·5 M. FROM EUGOWRA TOWARDS CANOWINDRA

14. Any other comments? NO RECORDS AVAILABLE OF ACCIDENTS AND FIGURES ARE APPROXIMATIONS.

    AS NEW CONSTRUCTION OF ROADS IS NOW ON 60 M.P.H. STANDARDS, FUTURE ACCIDENTS DUE TO FLOOD CONDITIONS OVER CAUSEWAYS COULD WELL BE OF A MORE SERIOUS NATURE DUE TO INCREASED VEHICLE SPEED.

Table 1:(cont'd.)

Details of Accidents Worthy of Further Study.

1.	Date of Accident	1938
2.	Names of persons involved or witnesses if possible	MRS. I. GORDON, DAUGHTER AND GRAND-DAUGHTER DROWNED
3.	Weather conditions at time of accident	HEAVY STORM
4.	Estimated depth of water on causeway	A FLASH FLOOD OVER THE CAUSEWAY WHEN CROSSING IN CAR WITH WATER LEVEL ONLY NORMAL FLOW. FLOOD DEPTH UNKNOWN BUT SUFFICIENT TO CARRY THE CAR 200 YARDS DOWNSTREAM
5.	Are photographs, reports or other sources of information available?	POLICE RECORDS

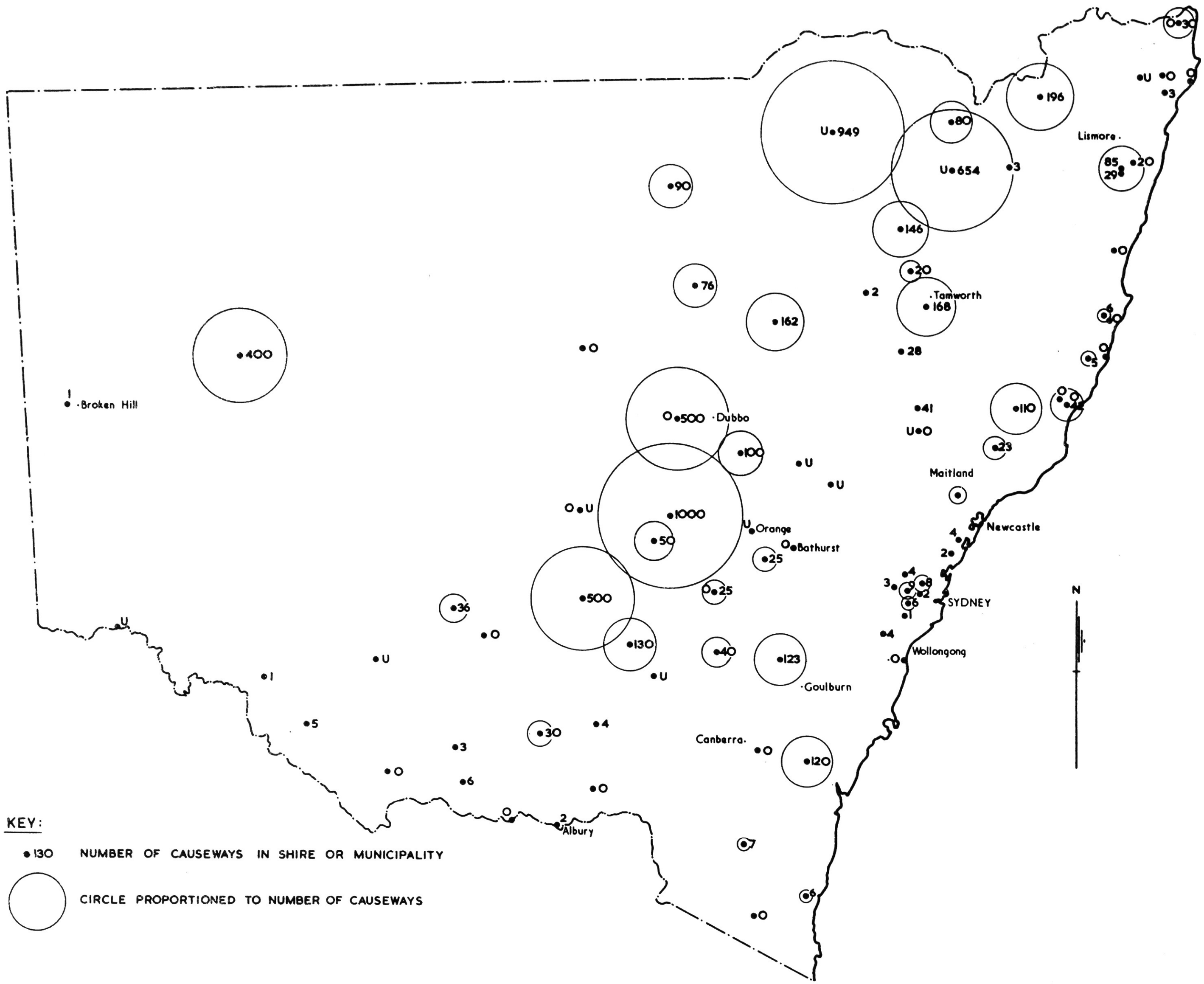


Fig. 1: Location map of known causeways in New South Wales.

3. Experimental Tests with a Model Car

3.1 Test Procedure

Extensive tests have been made with a model Falcon car in a laboratory test flume, and the car under test conditions is shown in Photographs 1, 2 and 3 and in Figure 2.

An accurate 1:25 scale model Falcon was obtained and suspended by fine threads both vertically and laterally. The threads passed over pulleys out of the flume to floats contained in burettes, and by this means horizontal and vertical loadings on the car were obtained. The tests consisted of placing the car in a steady uniform discharge in the flume over a wide range of depths and velocities of flow. The vertical and lateral reactions recorded by the burette floats are shown scaled up for a full size Falcon in Figure 3. The lines of equal force are reasonably consistent for both horizontal and vertical reactions.

3.2 Performance on a Floodway

The car will float in still water at depths greater than 22.3 inches. At this depth the boot is buoyed up and the rear wheels will float before the front wheels. (See Figure 6).

3.3 Performance on a Causeway

On a causeway the car stability will depend on the coefficient of friction that can be developed between the tyres and the causeway surface. The coefficient of friction to be adopted is considered under Section 4. Figure 4 shows the family of curves of equal coefficient of friction obtained from the ratio of the horizontal to vertical reactions in Figure 3. These curves are superimposed on to curves representing lines of equal discharge per foot width at full scale, and lines of equal Froude number. At higher depths and moderate velocities, notably at 20 inches and 5.5 ft. per second, the vertical reaction increases with increase of depth and velocity. This effect is considered to be due to aspiration and the slight vacuum developed produces a vertical force on the car. This upward hump in the curve is smoothed out in applying the results generally to other cars.

The interpretation of the curves is as follows:-

Suppose the car is capable of developing a coefficient of friction of 0.3 between the tyres and the flooded causeway, then the car will be on the point of slipping at a depth of 18 inches and a velocity of 5 feet per second or a depth of 11 inches and a velocity of 9 feet per second.

The horizontal reaction will consist of the resultant pressure and momentum forces acting on the sides of the car (H), (see Fig. 2).

The vertical reaction will consist of the following forces:-

The weight of the car, (W).

Car flotation due to the depth of water less any aspiration effect due to passage of water under the car (F).

Any vertical component of momentum force acting on the curved shape of the car side below the car door. (F^1).

The car and especially the wheels behave as an obstruction to the flow of water across the causeway. There is a backing up effect upstream of the car resulting in a lateral cross flow towards the front and rear ends of the car, with a concentration of flux around the ends of the car. The average discharge per unit width is reduced beneath the car but the wheels and rough undersurface of the car result in complex turbulence with hydraulic losses and a steep average hydraulic gradient beneath the car. Downstream of the car the water level is low and a cross flow occurs inwards from the ends of the car.

Model scales were as follows:-

Linear scale ratio = 1:25
A Froude relationship was assumed
Mass ratio = $1:25^3$ = 1:15,625
Depth ratio = $1:25^1$ = 1:25
Velocity ratio = $1:25^{\frac{1}{2}}$ = 1:5
Discharge ratio = $1:25^{5/2}$ = 1:3,150

4. Causeway Road Friction Factor

4.1 General

The following quotation is from a letter received from Mr. R. F. Jenkins, Technical Service Manager, Olympic Tyre and Rubber Co.

2. Model Falcon car under test.

3. End view of model Falcon car under test.

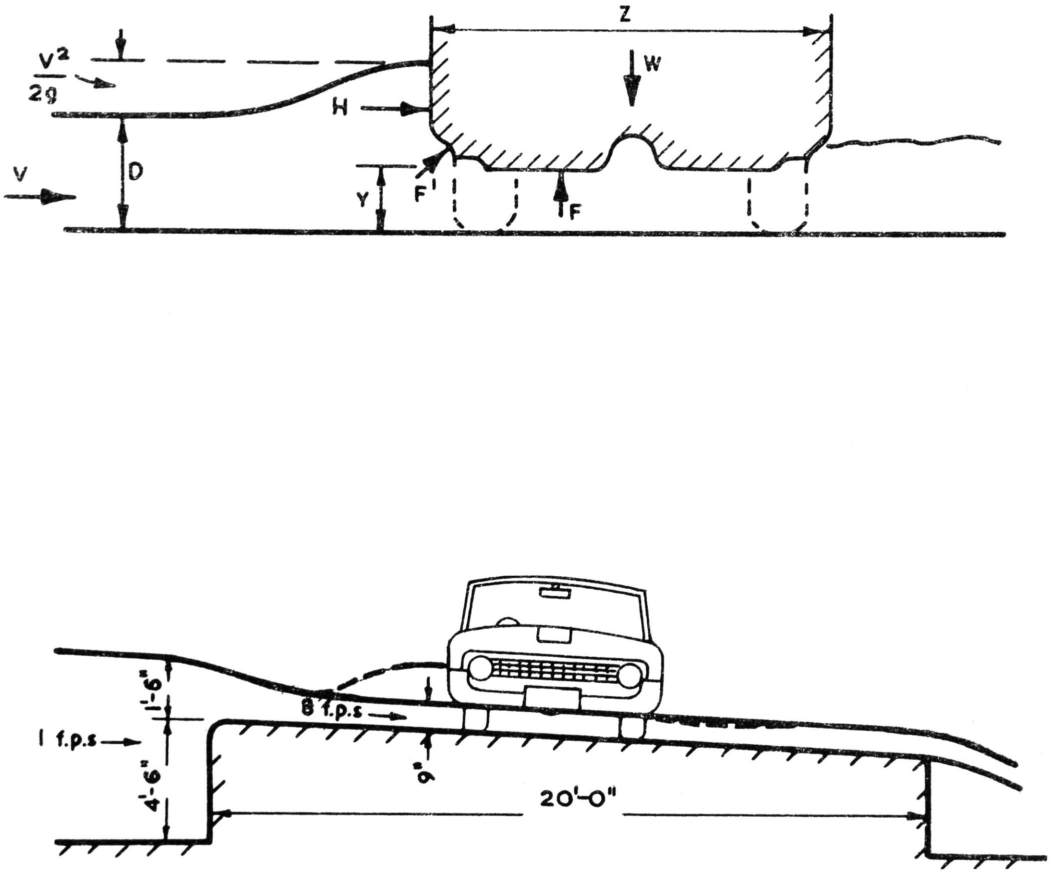


Fig. 2: Model car on elevated causeway.

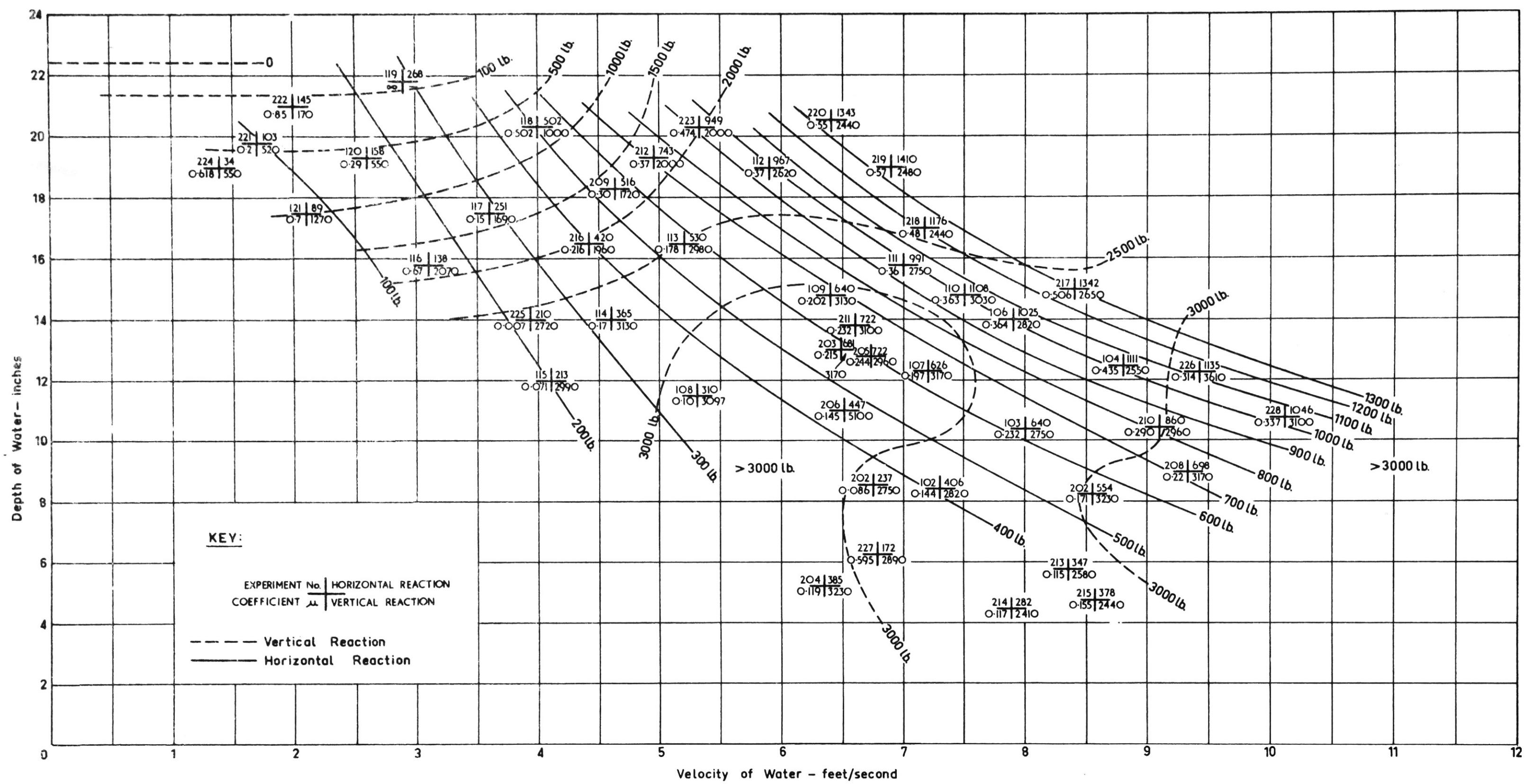


Fig. 3: Horizontal and vertical reactions of Falcon cars on causeways from model tests.

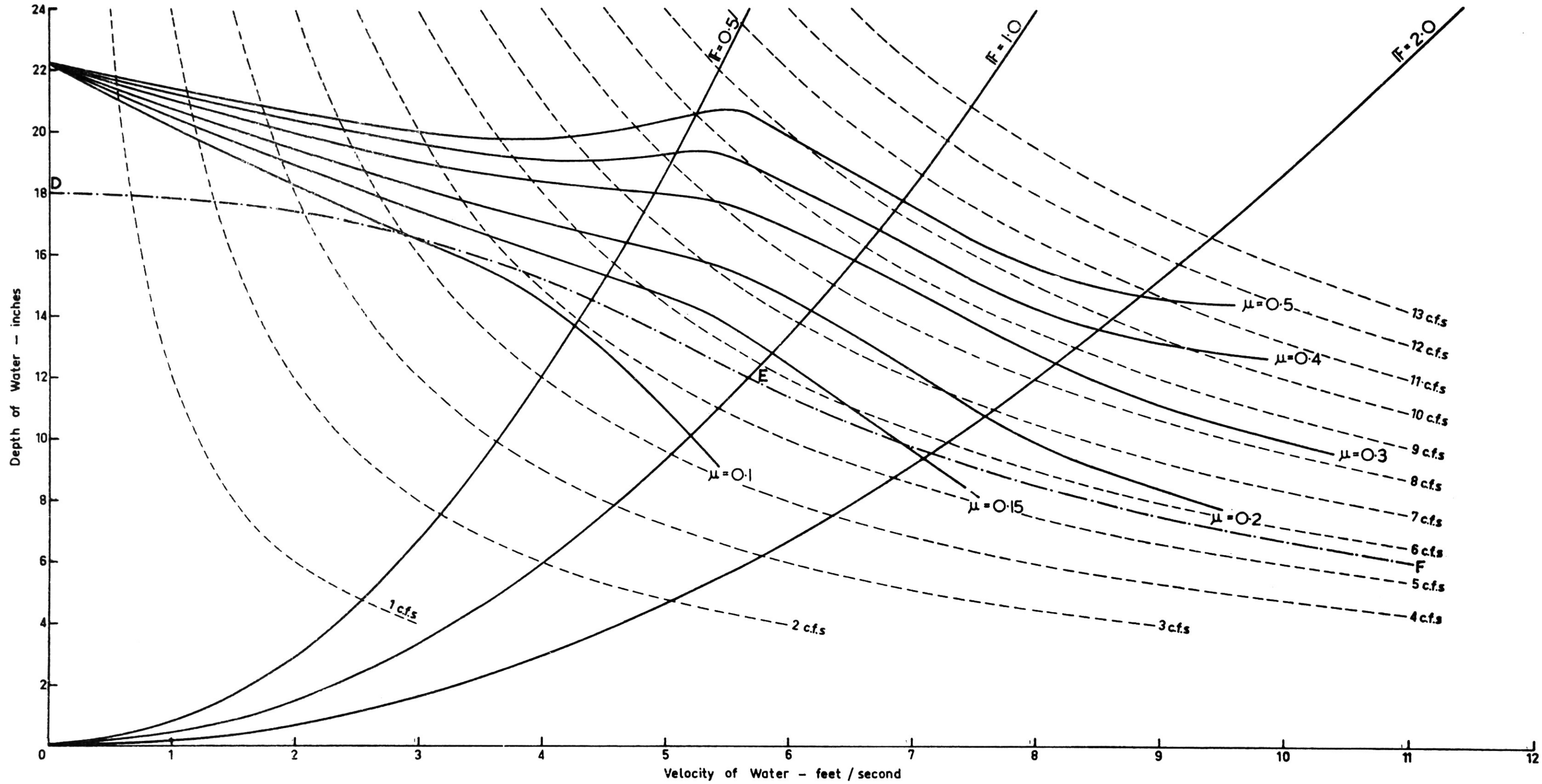


Fig. 4: Limiting stability for Falcon cars on causeways for various values of friction between car wheels and causeway surface.

Pty. Ltd., West Footscray, Victoria.

"We have not carried out any tests in the particular range in which you are interested so we cannot provide any actual results. We assume that at the depths of water quoted, the vehicle speed would be considerably reduced to something less than 5 miles per hour.

As far as we know from the published literature, no one has investigated the behaviour of tyres at low speeds in such depths of water. However, a considerable amount of information has been published by tyre manufacturers and Government Bodies on wet road friction and a list of some of the more comprehensive ones is attached.

The Road Research Laboratories in England have done a large amount of work on braking and cornering friction on various road surfaces. Some of this is at low speeds but at water depths up to 1/10 of an inch. This work is fairly well documented in their book, "Research on Road Safety".

Horne and others have used water depths up to 1.5 inches but mainly for braking tests. Most of their work concerns aeroplane tyres on flooded runways.

The wide range of figures published in these references shows how difficult it is to specify a coefficient of friction for a given tyre-road surface combination. It is doubtful if a reliable figure for a typical road condition could be estimated from these published results, let alone extrapolate them to the conditions which you specify.

In the 4 to 6 inches depth quoted, the tread pattern would be ineffective regardless of its state of wear. The treat pattern is only effective where the surface water in the contact area can be displaced into the tread grooves to give a dry contact between tyre and road. At the water depths of 4 to 6 inches, this displacement would not be possible and the tyre would behave similarly to a smooth one.

It is probable that the coefficient of friction will not be very high and this would be particularly so if the road surface was contaminated with silt or slime. Furthermore, of the available friction at the tyre-road interface, some will be required to provide traction and overcome drag due to the water leaving only part to resist sideways movement."

"Rubber, unlike other materials, develops its maximum friction when there is movement between it and the road. This maximum occurs at low speeds of sliding, and the friction is less at speeds higher or lower than this optimum. This means that any attempt to provide rapid acceleration (or braking) under these conditions could easily exceed the available frictional force and cause the wheels to spin (or lock) and further decrease the available friction.

Also, at the depths of water quoted, some hydrodynamic lift on the tyres could be expected. This would be more serious at higher speeds but even at the low speeds involved some reduction of frictional force might occur due to lower vertical load.

In our opinion, the only way to get a reliable figure would be to carry out direct measurement on typical causeways. Such a measurement could be made with an inclined wheel trailer similar to one used by the University of Queensland for road friction measurements.

We trust this information is of some use to you and regret that we are unable to give you the specific figures you require".

4.2 Value Selected

The sideway force coefficient selected has been taken from extensive tests carried out by the Road Research Laboratory in England from 1930 to 1936 and published as Road Research Technical Papers 1 and 2. (See References 2 and 3).

Some of the tests may be reasonably applicable to causeways because fairly smooth tyres were used giving poor drainage due to the lack of tread grooves with the small depth of water on the test road, which would probably have an effect comparable to slightly better tyres on a deeply flooded causeway.

The worst value of sideway force coefficient at 10 m.p.h. was $\mu = 0.48$. This occurred on a road with a tar and chip dressing after the chippings had worn off, or had immersed into the binder after hot weather. This situation could easily occur on a concrete causeway where an area of tar or bitumen had been applied, say, following repairs after settlement.

A reasonably low basic braking coefficient for a partly worn tyre on a smooth causeway surface on a wet country road was found to be 0.5 at a speed of 5 m.p.h.

The sideway force can be 10 pc. less, say 0. 45.

The slipping friction factor is less than the peak value before slipping commences, say 0. 36 from Table 2.

Table 2

Road Friction Factor

"Peak" coefficient before slipping	"Slipping" coefficient
0. 5	0. 4
0. 4	0. 32
0. 3	0. 24

The car may be subjected to collision with slippery floating debris such as wet straw catching against a wheel and being drawn between tyre and road so that a further reduction or safety factor should be introduced for this sort of contingency of say 20 pc. The resulting sideway coefficient of friction is $\mu = 0.3$.

A sideway force coefficient of 0. 3 has therefore been adopted. However, the absolute reliability of this value is very questionable, having regard to the expert opinion of Mr. R. F. Jenkins of the Olympic Tyre and Rubber Company.

The value of $\mu = 0.3$ is almost certainly adequate for most surfaces, and has the merit that it is realistic and enables design standards to be laid down which if followed would greatly reduce the danger of accidents on flooded causeways.

5. Hydraulic Characteristics of Cars

5. 1 Car Statistics

An analysis of car registrations has been made to classify vehicles in type classes so that any proposed safety measures will apply to the complete range of cars on the roads. Cars conveniently fall into seven classes which are shown in Table 3. The number in each class registered in 1966 and the percentage of the sales market this represents is shown in Table 4 and also shows the total registrations of all vehicles in New South Wales.

No consideration has been given to utilities, although these vehicles can be expected to follow fairly closely the corresponding sedan or station wagon regarding performance on flooded causeways. However, it will be seen later that utilities will be well covered by the proposals.

No consideration has been given to motor cycles; they clearly will not float. Buses will float and would be well advised to observe the proposed warning instructions for cars in view of the special responsibility encumbent on public transport. Most trucks will not float.

The cars in each class are similar in size, dimensions and shape regarding performance on a flooded causeway. Dimensional analysis was used to establish the car types which would sweep away most easily under the various conditions of water depth and velocity for a limiting coefficient of friction of 0.3.

5.2 Principle of Similarity

The experimental results obtained for the Falcon have been examined for application to the wide range of cars by dimensional analysis.

The floating forces were calculated accurately at various depths of flow for the Falcon, Volkswagen and the Holden. (See Figures 6, 7 and 8). These results were compared for all cars by analysis of dimensions, weights and shapes of cars. The dimensions and weights were taken from the "Autocar", "International Buyers' Guide", (Ref. 10). Other dimensions and shapes were taken from the "Motor", London "Road Test Digests", (Ref. 11), as well as from information supplied by the car manufacturers.

The force diagram is shown on Figure 2 where

V = velocity of water in flume
D = depth of water in flume
X = length of car
Y = a vertical height, nominally the height of the skirt above the causeway surface and adjusted to minimise the effect of the corner shape of the body work in that area.

Z = width of car
F = flotation force less any effect due to aspiration
F^1 = vertical component of momentum force resulting from the corner shape below the car door
μ = Coefficient of friction between tyres and causeway
r = Scale ratio between any car and Falcon
l_r = Scale ratio for length
F_r = Vertical force ratio = $l_{xr} \times l_{yr} \times l_{zr}$
H_r = Horizontal force ratio = $l_{xr} \times l_{yr}^2$
$\mathbb{F}_r$ = $1 = V_r^2 / l_r$, assumed Froude relationship
H = μ (W-F-F^1)

When $l_{xr} = l_{yr} = l_{xr}$ a simple scale relationship exists.

No problems arise until $l_{yr} = l_{zr}$

Table 5 shows the scale ratios adopted to relate tests on the Falcon to the various representative members of the seven classes of cars. Having discounted the obtrusive details of trim and styling, these different cars are rather similar when considered as geometric obstructions impeding the flow of water. This is demonstrated by comparing Figures 9, 10, 11, 12 and 13.

A scale weight is determined for each car with respect to the Falcon, and a shift in the value of μ obtained to make allowance for the actual weight of the car. A further shift in the μ value was made to compensate for the ratio in weight acting between the front and rear wheels; this effect was approximately 10 pc. in the case of cars in Class 3 and 15 pc. in case of cars in Class 4. The maximum effect was found to be 0.5 inch of flotation depth at low velocities.

A further correction has been made where necessary for the up-lift force due to the rate of change of momentum of the flow impinging on the curved side of the car between skirt and sill. The extreme range of this effect was found to be 0.6 inch difference in flotation depth.

The limiting stability on causeways for more floatable cars is shown on Figure 5 for a coefficient of friction of 0.3.

Table 3.

Registrations of New Cars in New South Wales in 1966, Classified for Performance on Flooded Causeways

Class No.	Description of vehicles which includes Sedans and Station Wagons	No. regd. in 1966	Pc. of Market
1.	Average sized conventional cars including Holden, Valiant, Falcon and similar imported cars.	69,359	63.3
2.	Small conventional cars including Hillman, Cortina, Toyota Corona and Viva.	16,159	14.7
3.	Front wheel drive cars including Morris 850, 1100 and Austin 1800.	14,759	13.5
4.	Rear engined cars including W.V., Imp and Fiat 600D.	5,623	5.1
5.	Large conventional American size cars including Chevrolet etc.	2,210	2.0
6.	Sports cars including Triumph, MG, Sprite, Honda, Colt.	1,085	1.0
7.	Others, including Land Rover etc.	480	0.4
	TOTAL	109,675	100.0

Taken from the Commonwealth Bureau of Census and Statistics, Canberra, Aust.

Table 4.

Total Registrations of all Vehicles in New South Wales, November, 1966.

Cars	907,414
Station Wagons	175,358
Utilities	126,829
Panel Vans	58,363
Trucks	99,942
Other trucks	3,609
Buses	5,984
Motor Cycles	20,654
TOTAL	1,398,153

TABLE 5.

APPLICATION OF RESULTS OF TESTS WITH MODEL FALCON TO OTHER CARS

CLASS OF CAR	MAKE AND MODEL OF CAR (Generally the Sedan)	LENGTH X ft. ins.	VERTICAL Y ins.	WIDTH Z ft. ins.	WEIGHT W lbs.	FLOATATION DEPTH ins.	LENGTH SCALE l_{xr}	VERTICAL SCALE l_{yr}	WIDTH SCALE l_{zr}	FLOATATION DEPTH SCALE l_{yr}'	% DIFFERENCE BETWEEN l_{yr} and l_{xr}	ADOPTED SCALE l_r	FORCE SCALE SELECTED F_r	SCALE WEIGHT W'	F:R WEIGHT RATIO	μ SHIFT FACTOR	ESTIMATE OF MAX. % ERROR
1	Falcon XL	14-6	9	5-8	2688	22·3	1	1	1	1	0	1	1	2688	1·16 : 1	1	0
	Falcon 500	15-4	8½	6-2	3100	22½	0·945	1·12	0·92	1	22	0·96	0·87	3100		1	12
	Holden	15-1¼	8½	5-10	2682	21·8	0·96	1·12	0·975	1·02	17	1·0	1·0	2682	1·18 : 1	1	6
	Valiant Station Wagon	15-8¼	8½	5-9	2778	23	0·92	1·12	0·99	0·97	13	0·99	0·97	2778		1	5
2	Daihatsu	12-5¾	6½	4-9	1715	–	1·16	1·38	1·20	–	15	–	–	–		–	–
	Fiat 124	13-2½	6	5-0	1800	18	1·10	1·50	1·13	1·24	33	–	–	–	As	–	–
	Ford Cortina	13-9¼	8	5-2½	1700	19½	1·05	1·12	1·09	1·14	3	1·10	1·28	2100		0·82	5
	Hillman Minx	13-5½	7½	5-0¾	2182	22½	1·08	1·20	1·12	1·0	7	1·12	1·45	1850	Class 1	1·18	8
	Toyota Corona	13-4	8	5-1	2040	20	1·09	1·12	1·11	1·11	1	1·11	1·35	2000		1·02	2
	Vauxhall Viva	12-11	8	4-11¾	1564	18	1·12	1·12	1·14	1·24	2	1·13	1·43	1880	say	0·83	1
	New Holden Torana	13-5½	8	5-3	1698	18	1·08	1·12	1·08	1·24	4	1·10	1·31	2050	1·17 : 1	0·83	2
	New Cortina	14-0¼	7½	5-2½	1848	18	1·03	1·20	1·09	1·24	17	1·13	1·44	1870		0·99	10
	Bellett	13-2½	8	4-11	2030	19	1·10	1·12	1·12	1·17	0	1·12	1·38	1950		1·04	2
	Hillman Hunter	14-1½	7½	5-3½	2060	19	1·03	1·20	1·07	1·17	12	1·10	1·32	2040		1·0	8
3	Morris Mini	10-0¼	6	4-7½	1398	17½	1·45	1·50	1·23	1·27	22	1·3	2·68	1000	1·46 : 1	1·3	15
	Morris Mini Van	10-9⅞	6	4-7½	1334	16	1·34	1·50	1·23	1·40	22	1·3	2·48	1080		1·13	7
	Morris 1100	12-2¾	6	5-0½	1782	19½	1·18	1·50	1·12	1·14	34	1·26	1·98	1360	1·48 : 1	1·31	15
	Austin 1800	13-8¼	6	5-6¾	2535	–	1·05	1·38	1·02	--	35	1·14	1·48	1820		1·39	12
4	Fiat 600 D	10-9	6½	4-3½	1334	19	1·35	1·38	1·33	1·17	4	1·35	2·48	1080		1·24	3
	Hillman Imp	11-7	8	5-0¼	1523	19	1·25	1·12	1·13	1·17	1	1·15	1·58	1700		0·90	10
	Volkswagen	13-4	7	5-0½	1720	21·3	1·09	1·28	1·13	1·05	13	1·15	1·58	1700	1·70 : 1	0·86	10
5	Chevrolet Impala	17-9½	8½	6-7½	3870	–	0·814	1·12	0·85	–	32	–	–	–	As Class 1	–	–
	Dodge Monaco	18-0¼	8½	6-7	4132	–	0·804	1·12	0·85	–	32	–	–	–	say 1·17 : 1	–	–
6	M.G Midget	11-5½	6½	4-7	1575	18	1·265	1·38	1·24	1·24	11	1·28	2·16	1250	As Class 1	1·26	10
	Triumph Spitfire	12-1	6½	4-9	1568	18	1·20	1·38	1·20	1·24	15	1·25	1·99	1350	say 1·17 : 1	1·16	10
7	Light Wankel Car	10-9	6½	4-3½	1080	15	1·35	1·38	1·33	1·48	4	1·35	2·48	1080	1·16 : 1	1·00	3

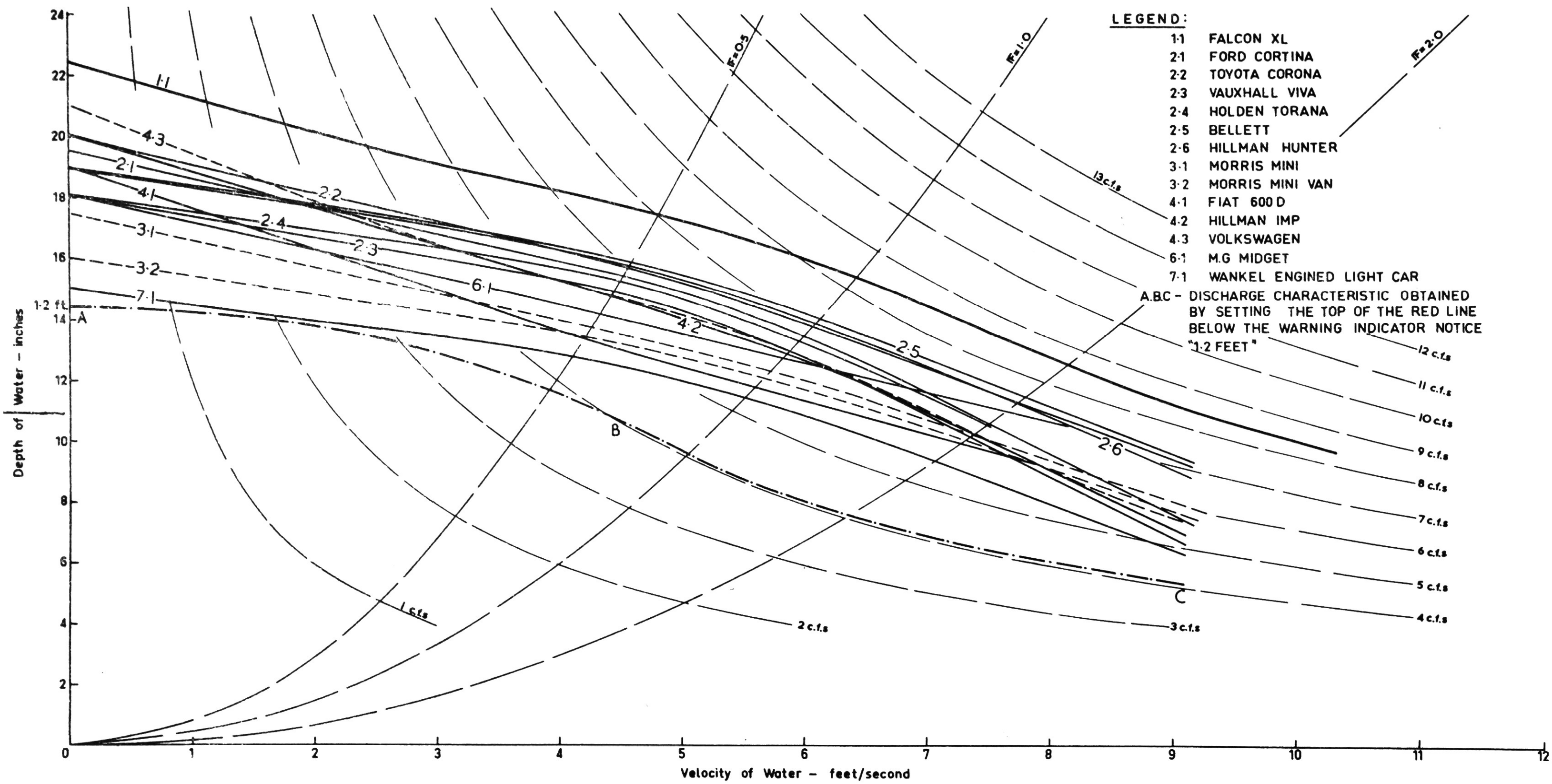


Fig. 5: Limiting stability on causeways for more floatable cars for coefficient of friction μ = 0.3.

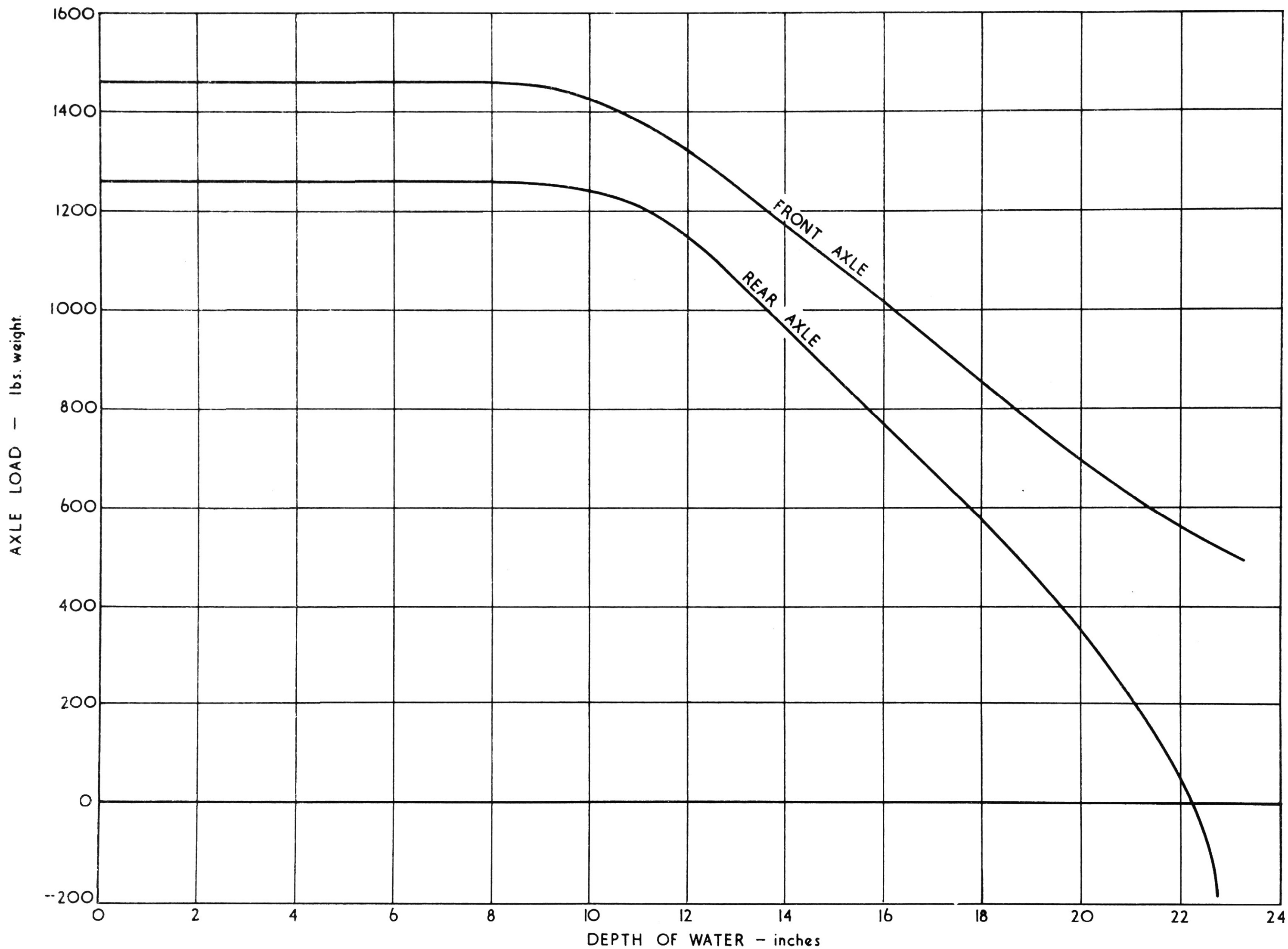


Fig. 6: Buoyancy in still water - Falcon.

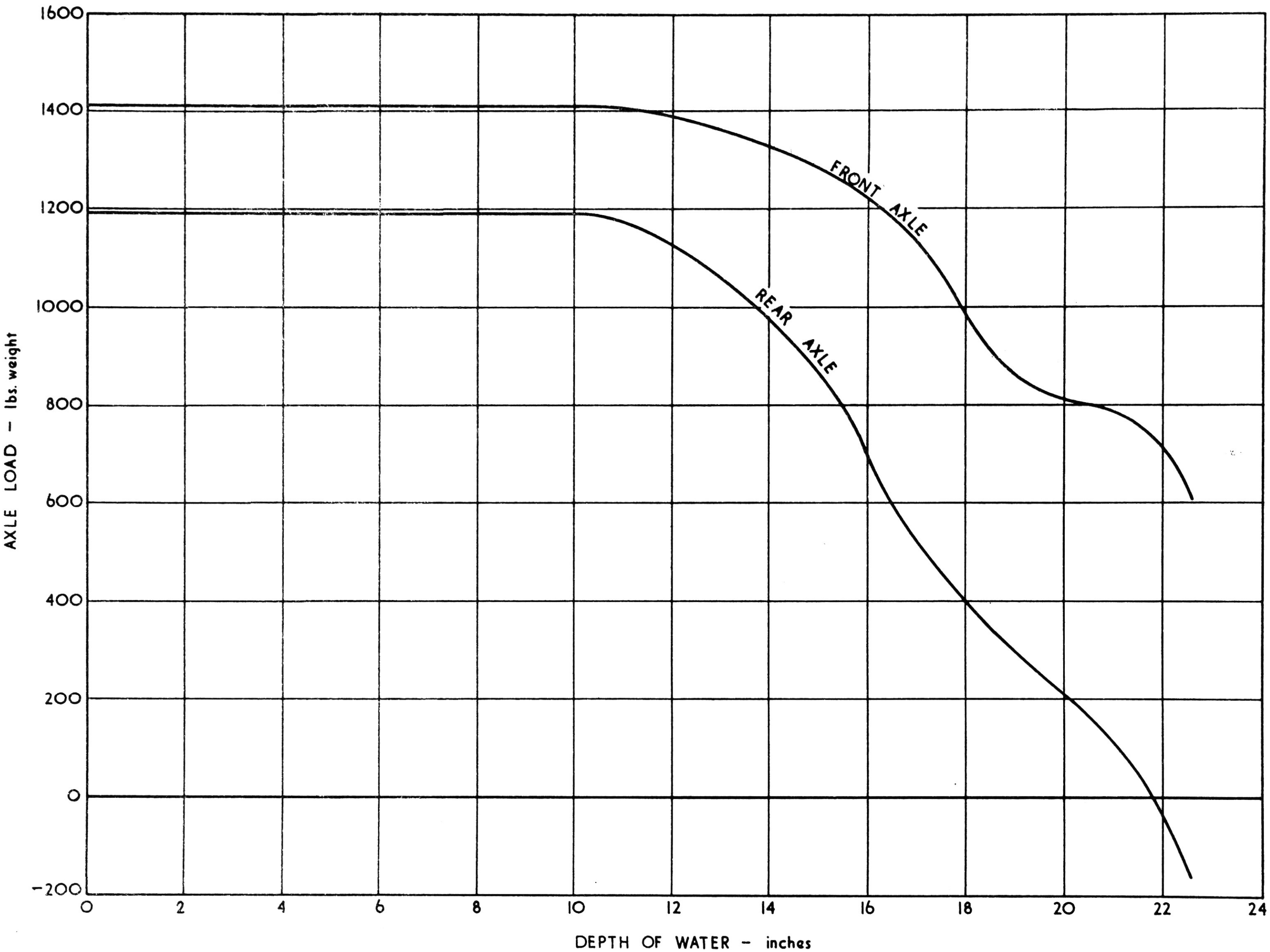


Fig. 7: Buoyancy in still water - Holden.

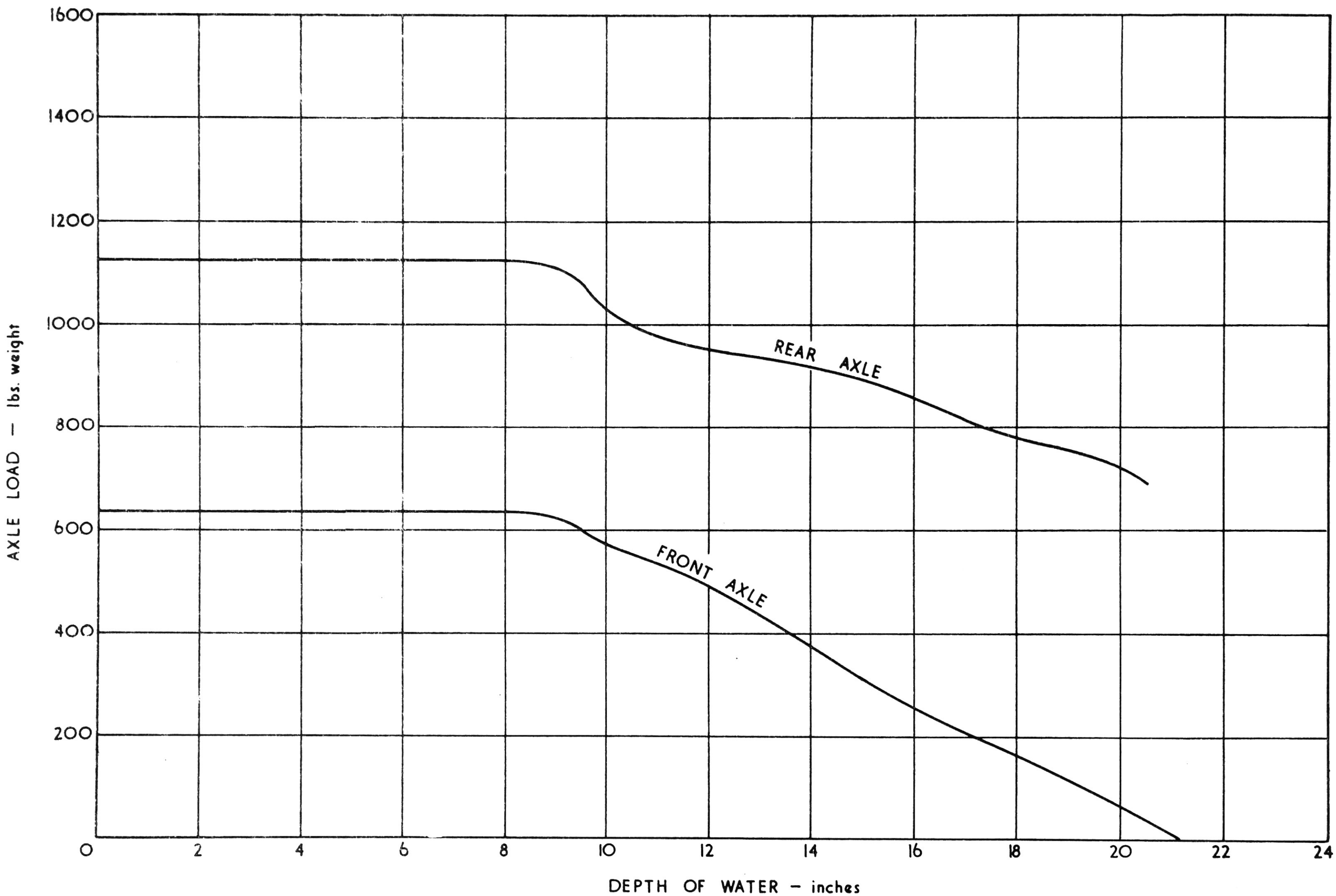


Fig. 8: Buoyancy in still water - Volkswagen.

5.3 Class 1. Medium Size Conventional Cars

The Falcon is a typical member of Class 1. This class represents 63 pc. of the market. Although many accidents have occurred on causeways with medium sized conventional cars, in fact this group will float less easily than several other classes due to the high road clearance and substantial weight.

5.4 Class 2. Small Conventional Cars

This class has been dealt with in more detail in Figure 5 because some members of the group have extreme characteristics. For instance, the weights of the Ford Cortina and Vauxhall Viva are remarkably low in relation to the size of the car. The weight of the Cortina scaled down from the Falcon would be 2,100 lb. but in fact the weight is only 1,700 lb. The new models fall more in line as scale models of Class 1, notably the new Cortina, Torana, Hillman Hunter and the Toyota Corona. This class represents some 14.7 pc. of the market.

Class 2 is worthy of special note because generally it appears to be a class of car which is undergoing fast development. The large international car companies appear to be anxious to produce a car which will most economically convey a small family group and with 10 or 15 cubic feet of usable boot space. A new model will generally be larger or lighter due to improved techniques of structural design and construction.

5.5 Class 3. Front Wheel Drive Cars

Thisclass consists of the B.M.C. front wheel drive cars comprising 13.5 pc. of the market in New South Wales. Table 5 shows that of the cars at present on sale in quantity, the Morris Mini-Van is most likely to float across a flooded causeway. However, the Mini-Van contains a fairly heavy engine and it is considered that a worse case in the immediate future is likely to be a car of the same shape as the Mini-Van but fitted with a light weight Wankel type engine. In this connection, it should be noted that there are several such engined cars in current production in Germany and Japan, notably the N.S.U.

5.6 Class 4. Rear Engined Cars

These cars are most susceptible to sliding across a flooded causeway at velocities of 4 to 6 feet per second. The Fiat 600D is worse in this respect than any other car at present on sale in quantity. However, a similar car with the new Wankel engine will be worse. The boundary curve on Figure 5 refers to such a car.

5.7 Class 5. American Cars

These cars compare closely with medium sized Australian cars in their performance on a flooded causeway. This class represents 2.0 pc. of the market in New South Wales.

5.8 Class 6. Sports Cars

The sports carsin Class 6 tend to be heavy because a stout body structure is provided and a heavy engine in relation to their size. The flotation volume is not large.

5.9 Class 7. Others

Class 7 includes a few home designed and home made fibre glass cars which defy categorisation. One such car was swept away on a causeway and the driver lost his life. Drivers of such cars should not attempt to cross a causeway with even a very small discharge of water flowing over it.

Most other members of this class have high and heavy bodies such as Land Rovers.

5.10 Discussion - New Lightweight Cars

The large car companies are competing to produce a car which will convey passengers and luggage more economically. New models will be lighter or larger due to improved techniques of structural design and construction. The reduction of dead weight permits the use of a smaller engine. As road surfaces improve generally due to accelerating highway construction programmes, a lower body clearance becomes more acceptable to the public. A lower body allows better cornering and style.

General Motors, the largest manufacturer, has recently introduced a new Opel Record in Germany with a tilted engine and lower transmission line and will perhaps eventually include this improvement in future Holdens for the Australian market. These cars will float better than existing models.

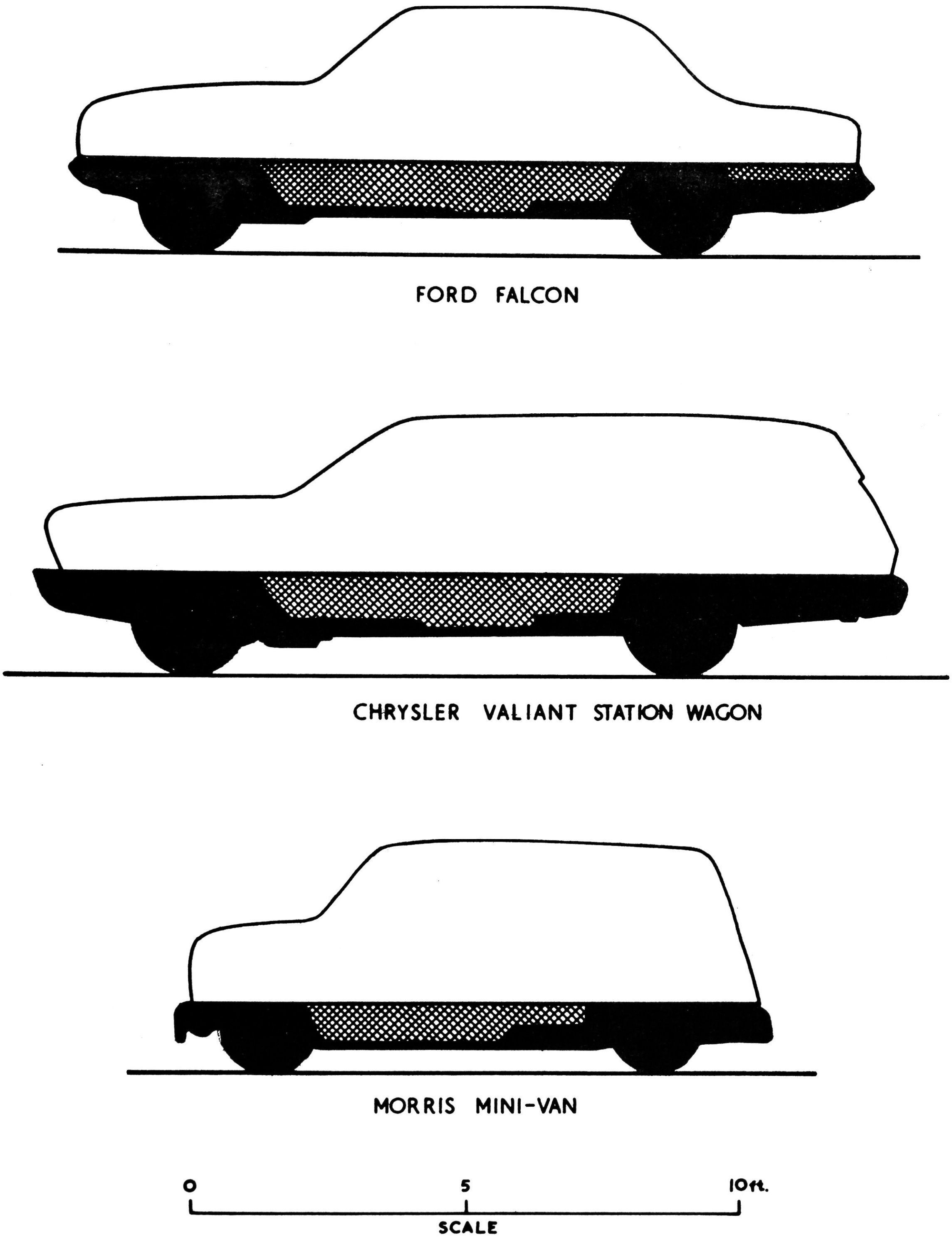


Fig. 9: Car elevations - Ford Falcon, Chrysler Valiant, Morris Mini-van.

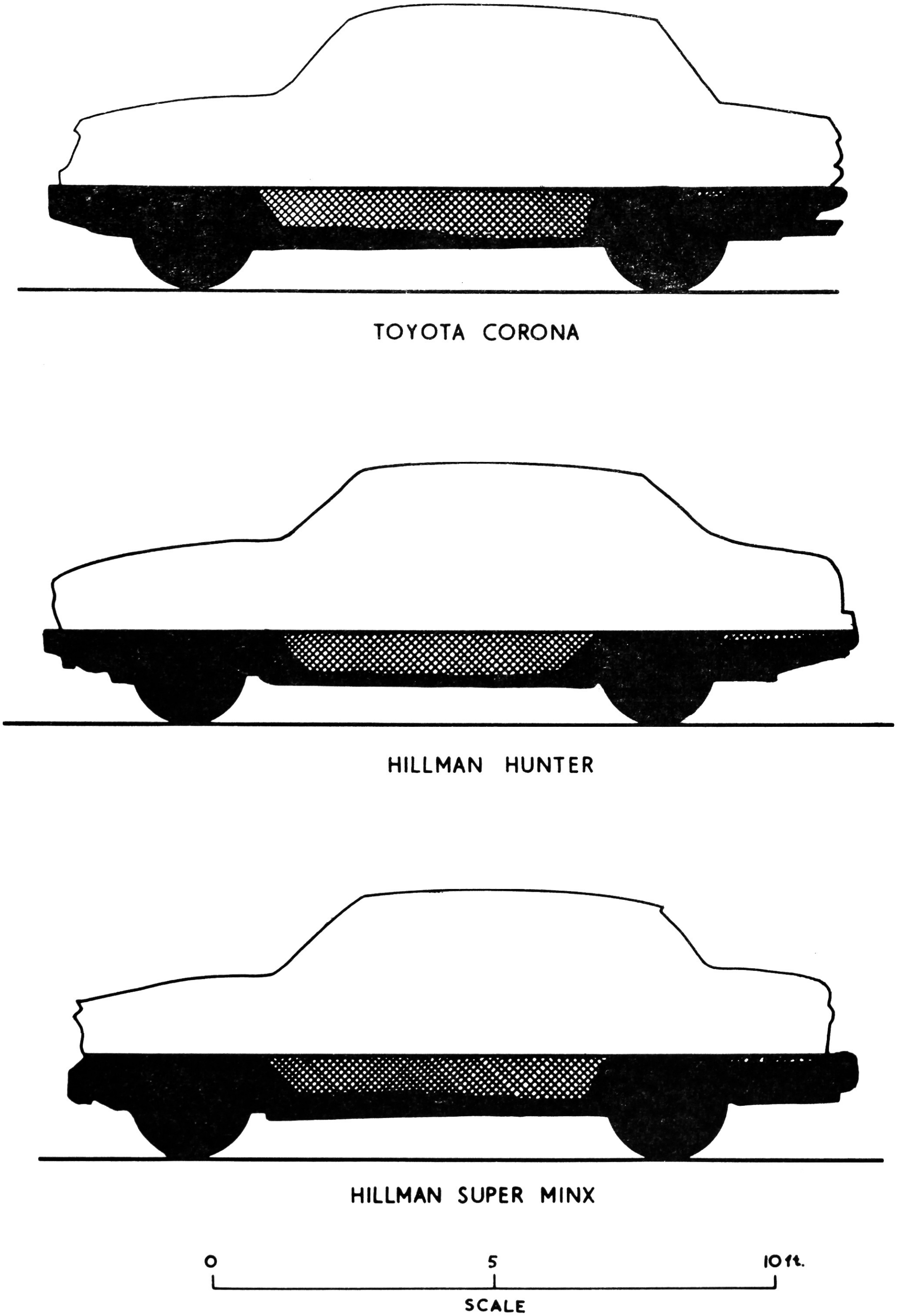


Fig. 10: Car elevations - Toyota Corona, Hillman Hunter, Hillman Super Minx.

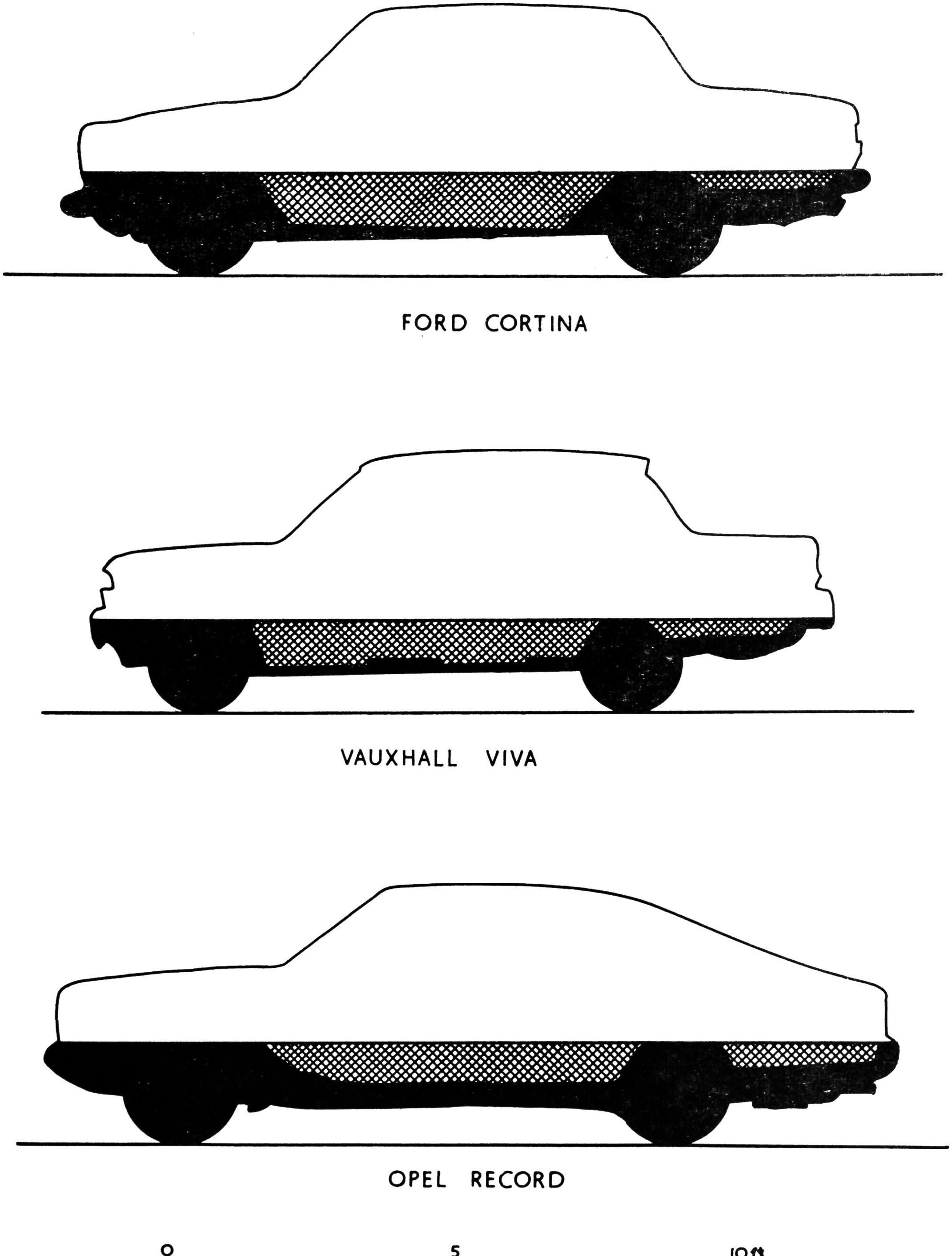


Fig. 11: Car Elevations, Ford Cortina, Vauxhall Viva, Opel Record.

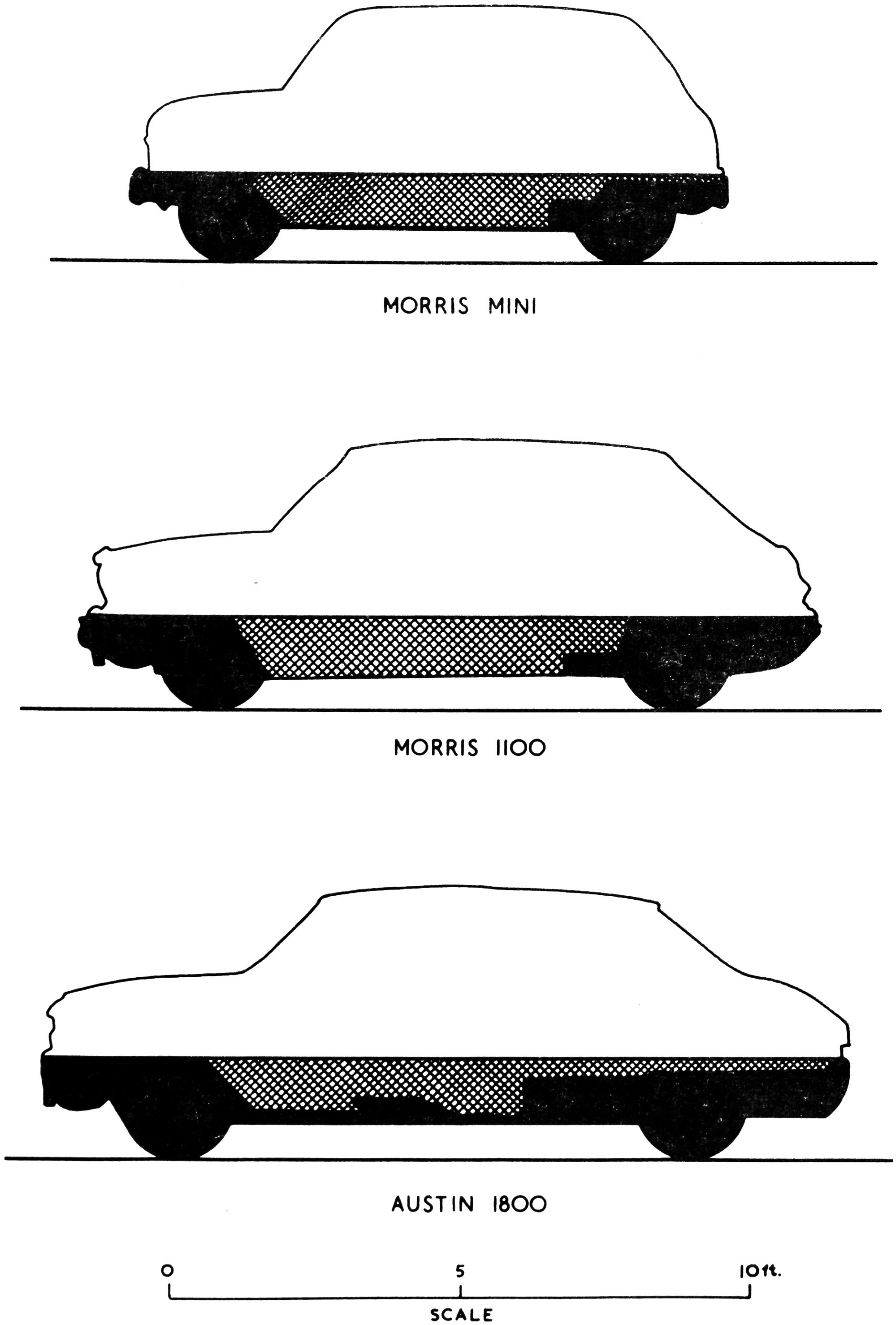


Fig. 12: Car elevations - Morris Mini, Morris 1100, Austin 1800.

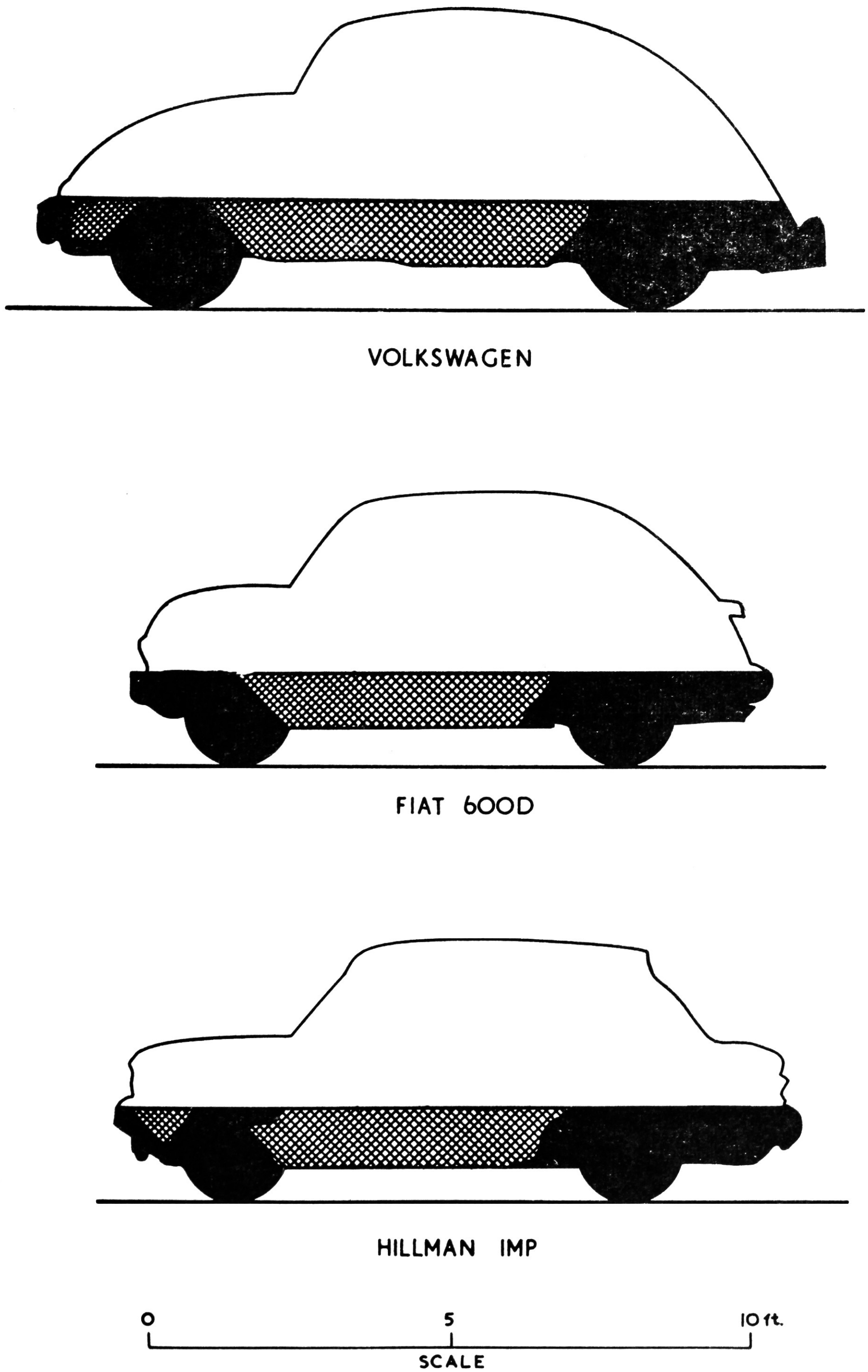


Fig. 13: Car Elevations - Volkswagen, Fiat 600D, Hillman Imp.

Manufacturers in several countries have introduced light cars with new forms of lightweight engines which has reduced the structural loading on the car body and will soon lead to lighter body structures.

It is therefore necessary at this stage to take a conservative view of the tendency of cars to float. There are currently 57 models of light cars on sale in Australia. (Ref. 29). No purpose is served by adhering to results obtained rigidly from the existing set of cars available to-day when new cars are introduced almost every week.

An attempt has been made rather to delineate a boundary curve by the principle of similarity beyond which the manufacturers are unlikely to proceed in the immediately foreseeable future.

6. Experimental Tests with Model Causeways

6.1 Flat Causeways

Extensive tests have been carried out on level broad crested weirs by Woodburn over the range of discharges and weir widths applicable for causeways in New South Wales. (Ref. 21). These tests are for causeways with square corners, radiussed upstream corners and downstream slopes both backed up and not backed up. (See Fig. 14).

It can be seen that on the level causeway standing waves will occur at Froude numbers close to unity, that is at critical depth. The waves may rise to 0.5 of the critical depth. Critical depth may occur at several locations across the causeway and these locations are sensitive to corner shapes and backing up effects on the causeway. The waves could have a serious effect on the stability of a car, by the introduction of extra lateral loading.

6.2 Causeways with Upstream Camber

Model tests were carried out on causeways with upstream camber 1 in 25. (See Figs. 15 and 16). Waves occur, but less than on a causeway with a level surface. Critical depth occurs at the downstream edge of the causeway. Waves may rise to 0.5 of the critical depth at immediately sub-critical velocities. The effect of these waves on cars would depend on the exact location of the car on the causeway. These waves tend to instability which could result in a buffeting effect on a car.

6.3 Causeways with Downstream Camber

Model tests were carried out on a causeway with downstream camber of 1 in 25. (See Figs. 17 and 18). Critical depth occurs close to the upstream edge. Flow across the causeway is super-critical, smooth, stable and free from waves. If a side slope was provided instead of the "square" corner, the critical depth location would be moved upstream off the carriageway. Tests were also carried out by Woodburn (see Figs. 19 and 20). Where the down-stream energy level is high, a hydraulic jump can occur on the carriageway. This must be avoided on a causeway.

6.4 Causeways over Culvert Pipes

Model tests were carried out to determine the effect of culvert pipes under causeways. No appreciable change in depth occurred with pipes as compared with no pipes at all. It is not feasible to quantify results due to the wide range of combinations of cases that would have to be considered.

6.5 Conclusion

Causeways with downstream camber are to be preferred as providing smooth, stable flow, free from waves. However, suffic-ient difference between upstream and downstream energy levels must be available to prevent the formation of a hydraulic jump on the carriageway. Culvert pipes beneath the causeway section will not increase the depth of flow over the causeway.

7. Warning Indicator Notice

7.1 General

The proposed Warning Indicator Notice is shown in Figure 21. The proposed location and position is shown in Figures 23 and 24.

The notice would be large and easily read from a car travelling at 30 miles per hour. The driver may not always be aware that the causeway is flooded if travelling at night since the water often has a shiny black appearance not very different from a wet road surface. Many causeway accidents occur at night. The notice should be placed so that it is easy to see the iridescent red line caught in the beams from the headlights.

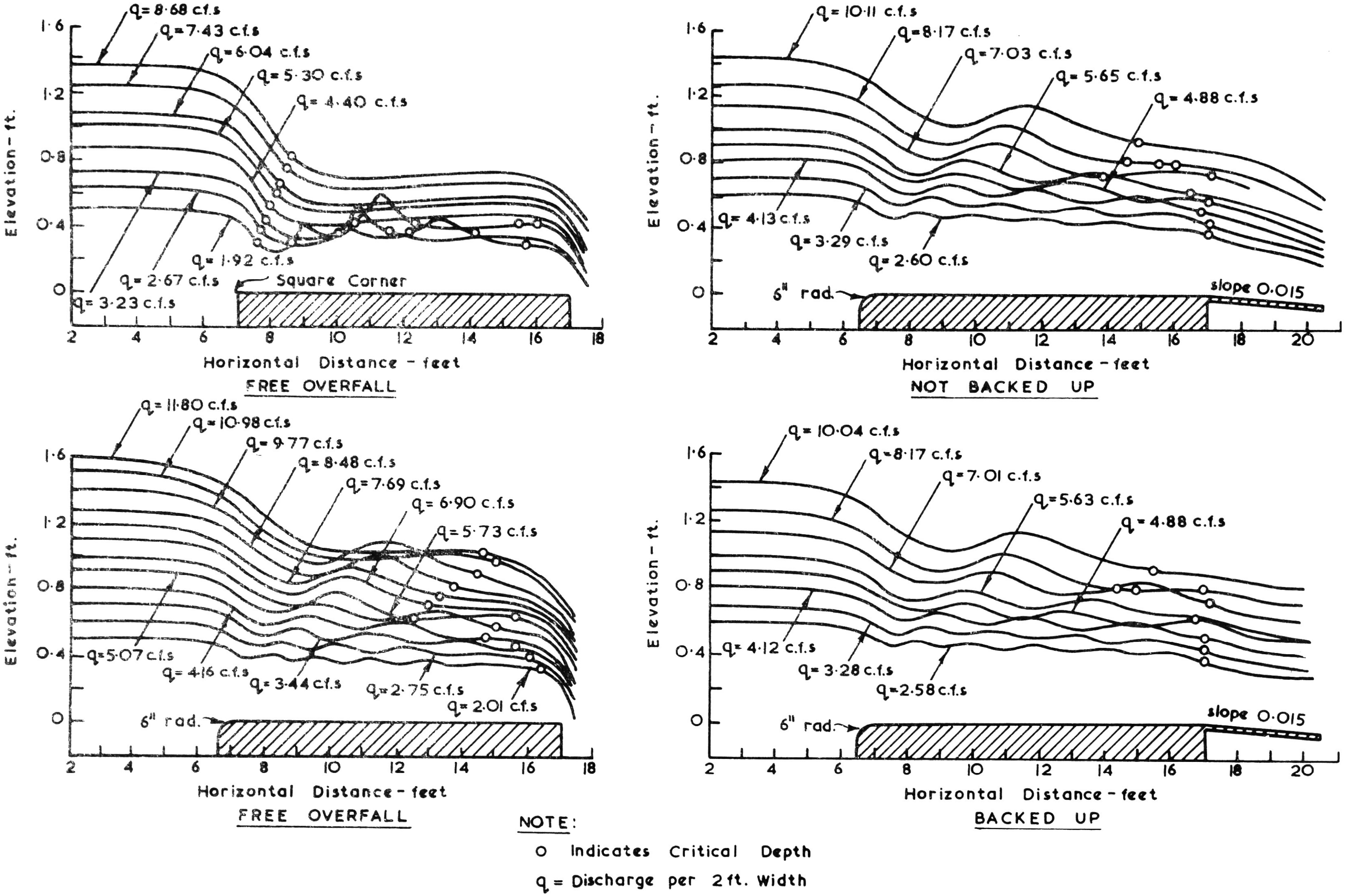


Fig. 14: Causeway flow characteristics - level surface (by Woodburn).

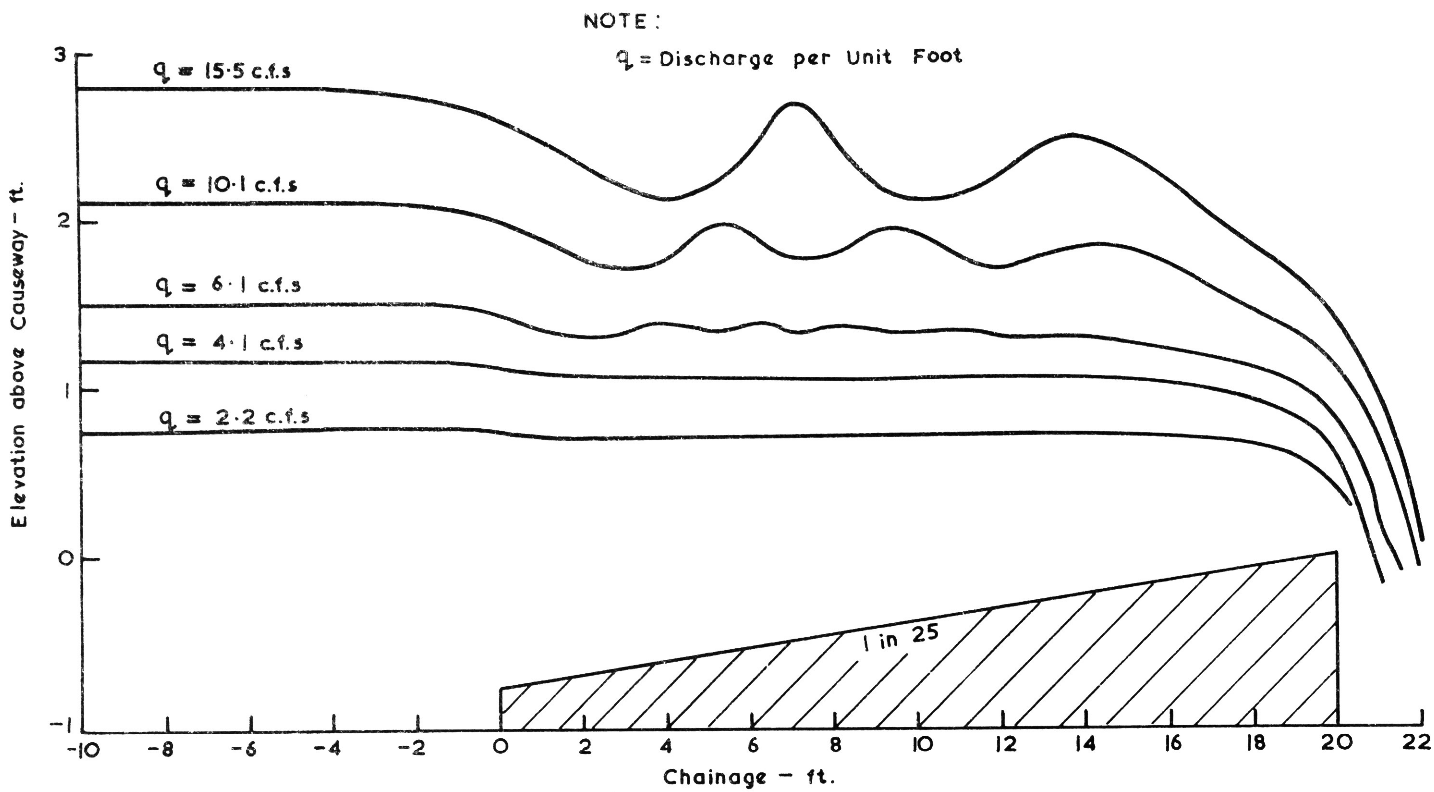


Fig. 15: Causeway flow characteristics - upstream camber.

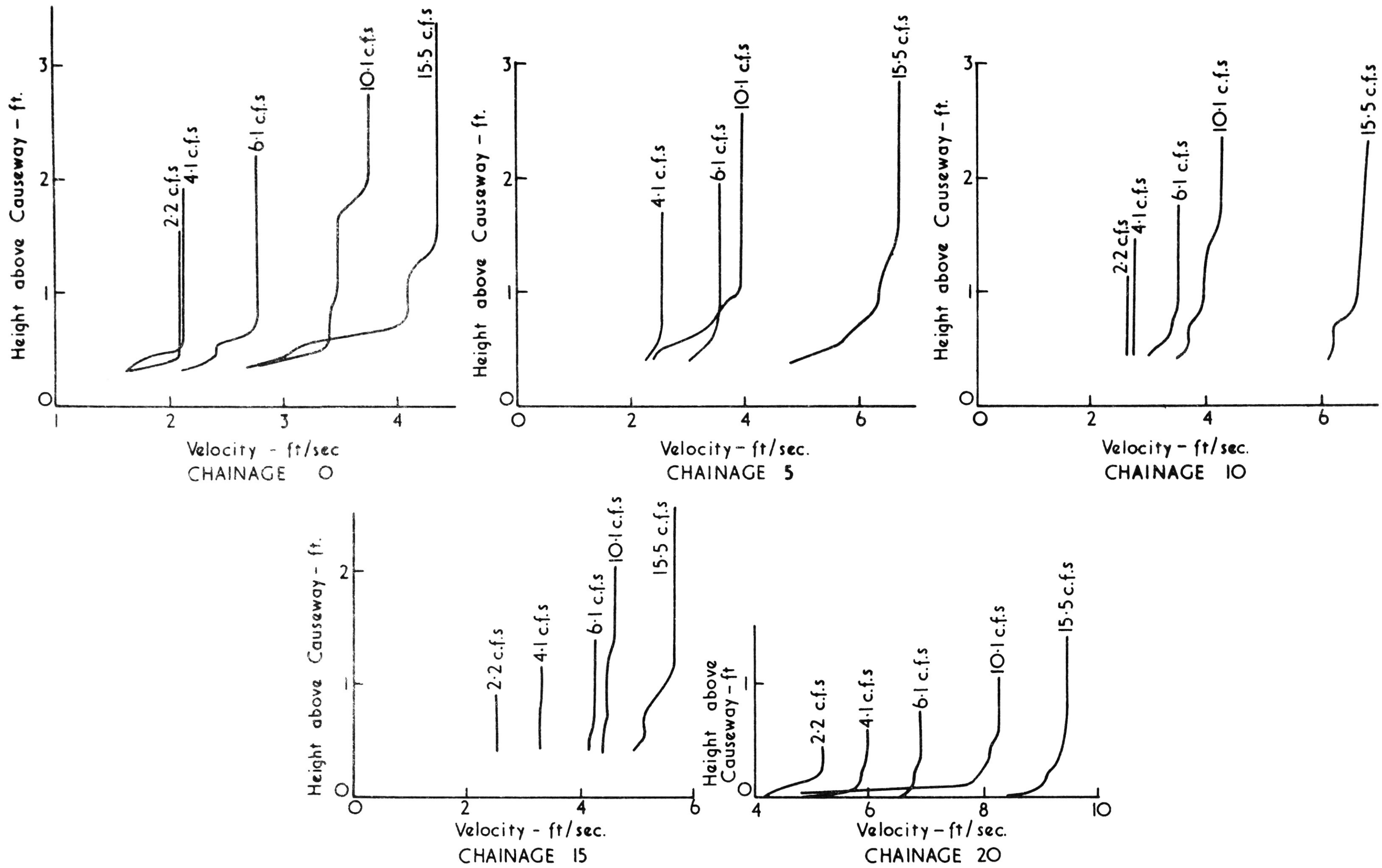


Fig. 16: Causeway flow characteristics - upstream camber velocity distribution.

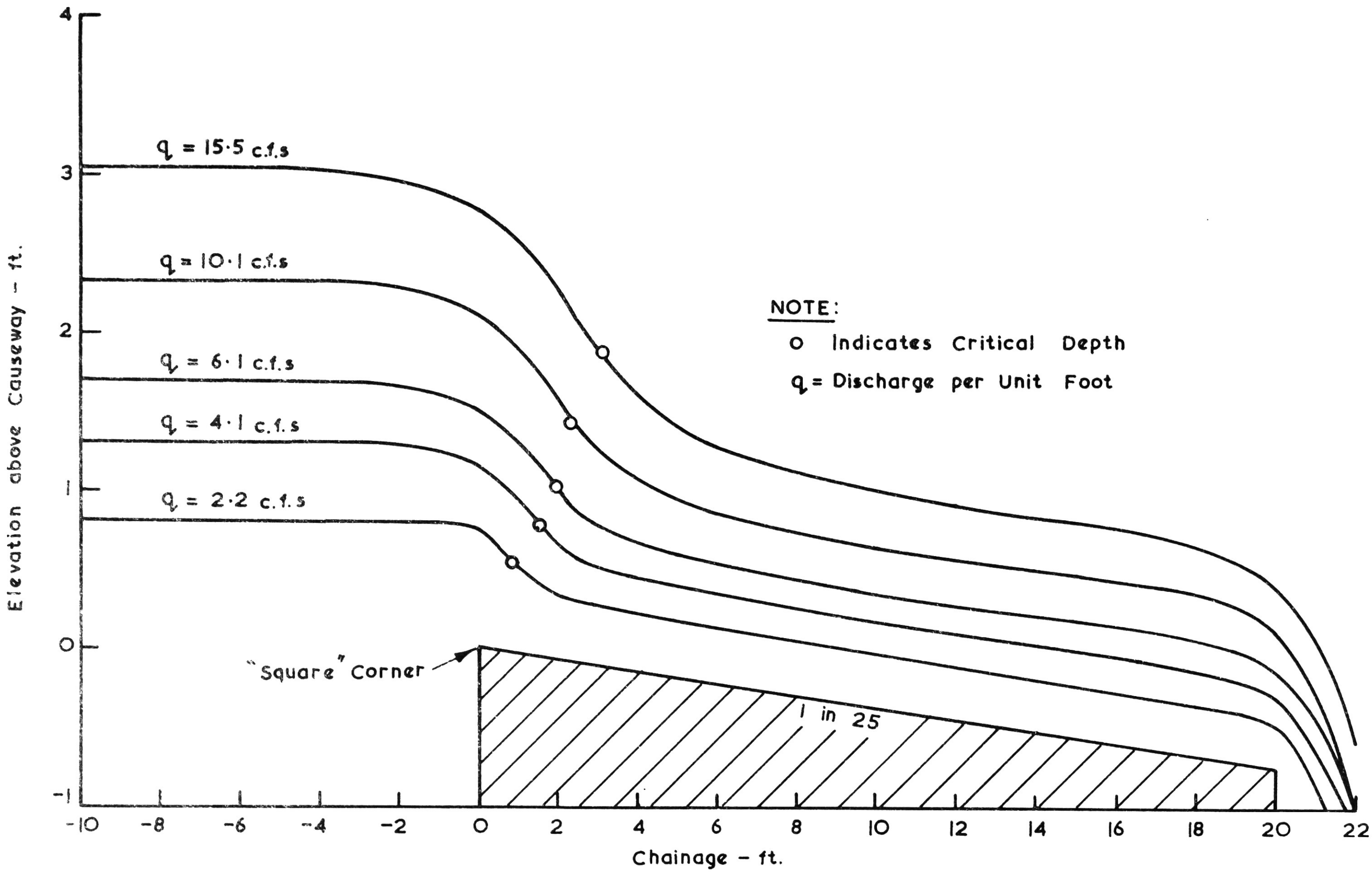


Fig. 17: Causeway flow characteristics - downstream camber slope 1 in 25.

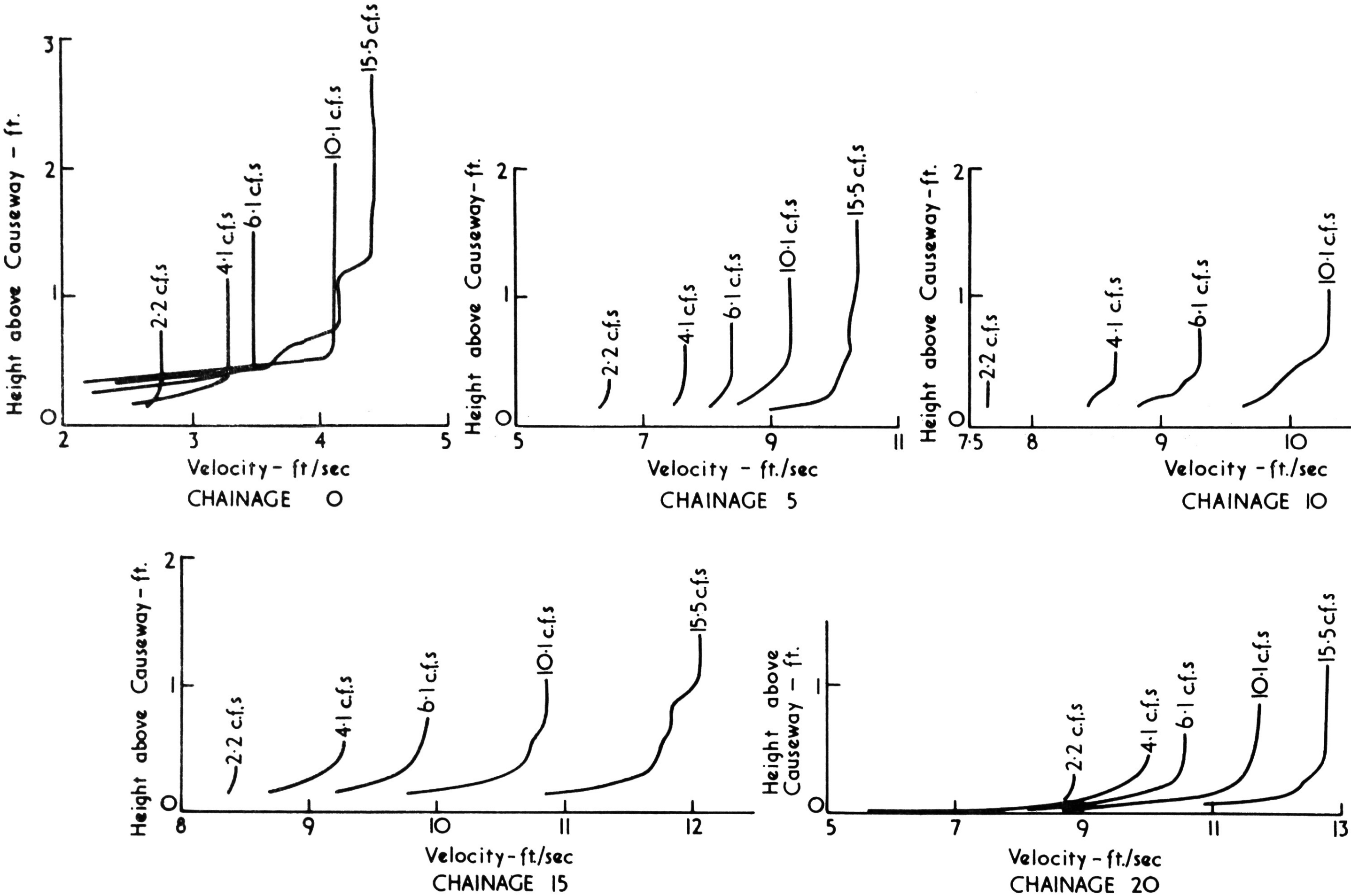


Fig. 18: Causeway flow characteristics - downstream camber velocity distribution.

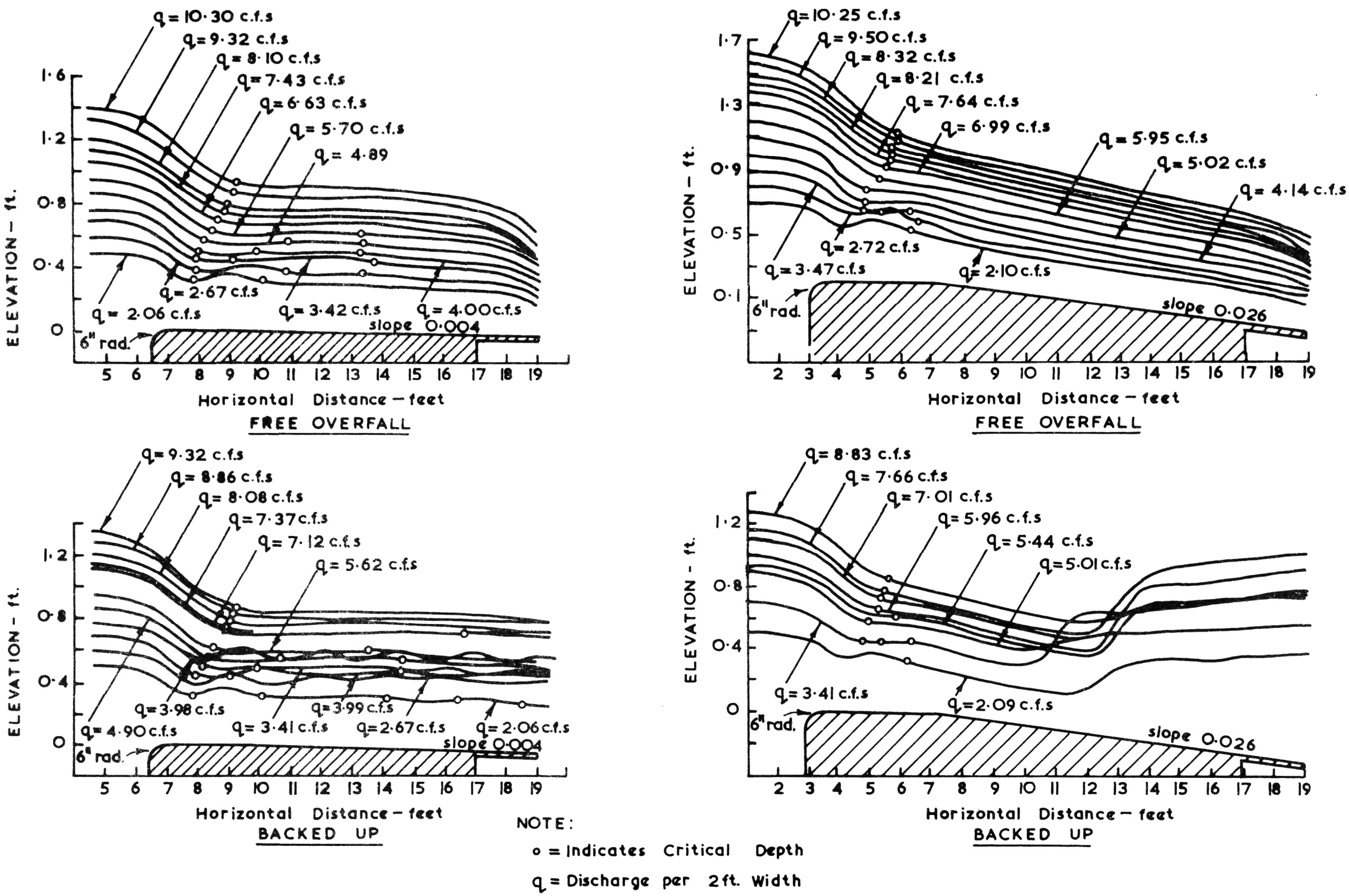


Fig. 19: Causeway flow characteristics - downstream camber II.

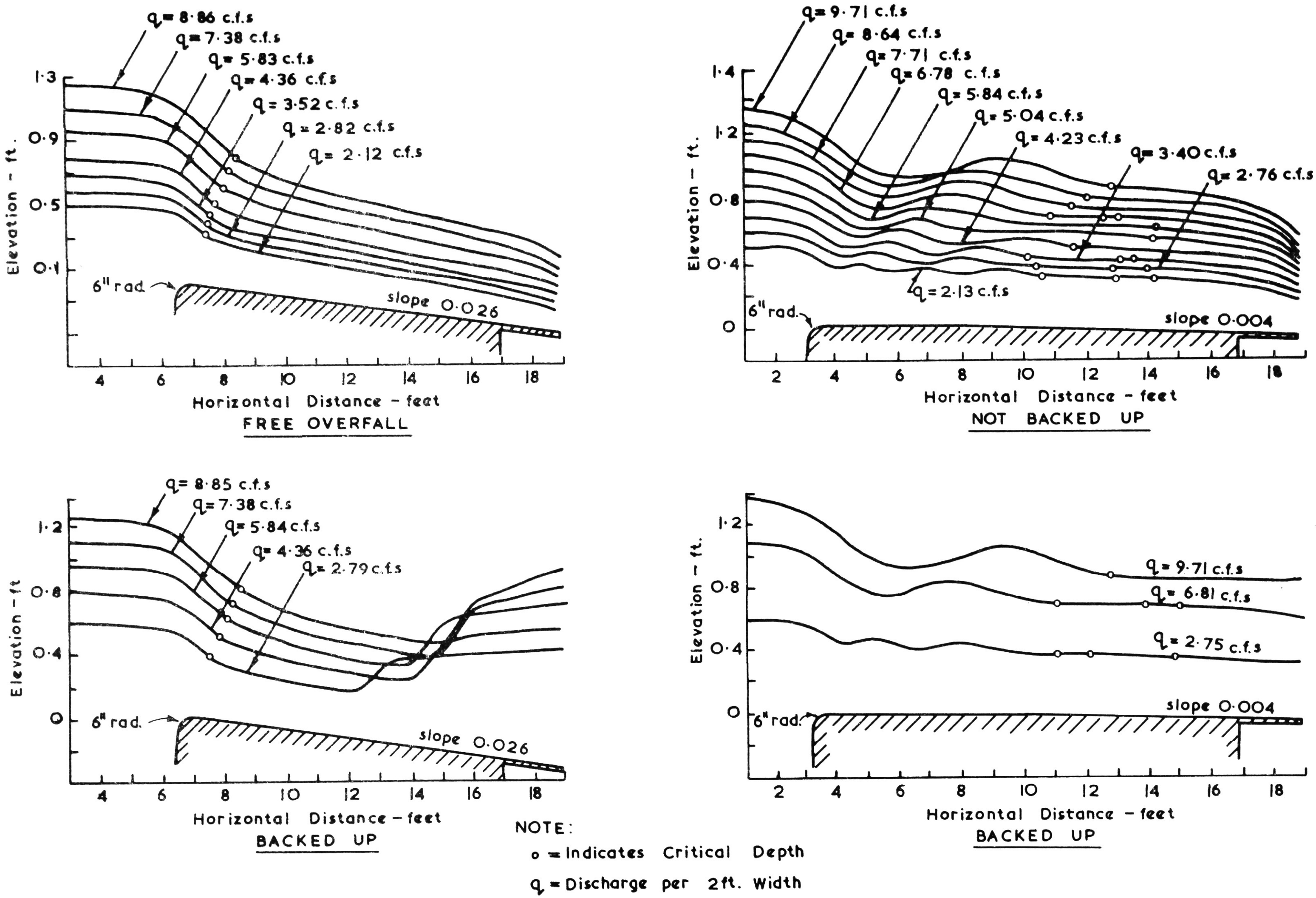


Fig. 20: Causeway flow characteristics - downstream camber III (by Woodburn).

The notice is intended to comply with S. A. A. standards. (See Refs. 24, 25 and 26).

The letters are black on a yellow background. The arrow is black on a yellow or white post. The red line would probably stand out best on a white background.

The notice is intended to be ready by all drivers of vehicles when approaching the causeway at all times. The notice is designed so that the driver can comprehend the meaning whilst approaching at a speed normal to the low classification roadway on which the causeway would be tolerated. The notice contains roughly the maximum number of words that can be comprehended in the time available under these conditions. Unfortunately, the average man in the street is not capable of reading and comprehending a technical instruction except of the simplest nature and therefore a more technical and detailed notice would be less effective in preventing accidents.

One must remember that some motorists can read only with difficulty and to many migrant drivers, English is a second language. The most effective road signs are the international signs consisting of a pictorial symbol which can be taken in at a glance.

The Warning Indicator Notice proposed is intended to be a simple reliable non mechanical device which if obeyed will give the best possible protection to the motorist.

7. 2 Operation of the Warning Indicator Notice

The Warning Indicator Notices should be located some 10 feet from the edge of the carriageway, one at each end and both upstream of the causeway as shown in Figure 24. The foot of the notice post should not be above the general flood plain level and should not be isolated from the general level of the flood plain. This is to ensure that water standing at the foot of the post is in slack water which is connected to the general level of flood water on the flood plain.

The level of the red line below the Warning Indicator Notice must be at a suitable elevation to indicate a safe level for any vehicle at any position on the causeway.

The discharge characteristic ABC on Figure 5 is obtained by setting the level of the red line at 1.2 feet above the high edge of the causeway. At B, $\mathbb{F}$ = 1 and BC represents a supercritical discharge of 4 cusecs per foot width. 4 cusecs per foot width can only be tolerated at depths of water less than 0.8 ft., that is at supercritical velocities. Hence the maximum discharge per foot width of causeway combined with the continued use of the causeway by vehicular traffic is obtained by promoting supercritical flow on the causeway. As will be seen later, the designer must ensure that a hydraulic jump will not form on the causeway such as is shown in Figure 20. Subject to this elimination of a hydraulic jump, the red line can safely be set at the level of 1.20 feet above the high edge of the causeway.

7.3 Flat Causeways

Causeways with a level surface are shown in Figure 14. Referring also to Fig. 5, it can be seen that by setting the top of the red line below the Warning Indicator Notice at 1.20 feet, the discharge will be somewhat less than 4 cusecs per foot width depending on the coefficient of discharge of the weir section. With a profile as shown in Figure 24, the discharge will approach 4 cusecs per foot width. Standing waves will occur on the causeway at Froude numbers approaching unity. Flat causeways are therefore not recommended for not backed up conditions where critical flow and waves may occur at any place on the causeway. Where critical flow will drown out due to downstream obstructions, the flat causeway is better than a sloping causeway because the water depth will not exceed 1.20 feet at any place on the causeway for a setting of 1.20 feet on the Warning Indicator Notice.

The flat causeway should be used for drowned out conditions for instance on a floodway, or a causeway placed in a valley with low valley slope or with downstream obstructions. The downstream energy level should not be more than 0.2 feet below upstream energy level so that the Froude number will not exceed 0.5 on the carriageway.

7.4 Causeways with Upstream Camber

From Figs. 5, 15 and 16, it can be seen that cars may float at the upstream side of the causeway at discharges as low as 2 cusecs per foot width. The car may come to rest at the downstream edge of the causeway at discharges below 2 cusecs per foot width providing the car does not swing around. However, the car will almost certainly swing around because of uneven wheel loadings and other asymmetrical forces. For this reason, causeways with upstream camber cannot be

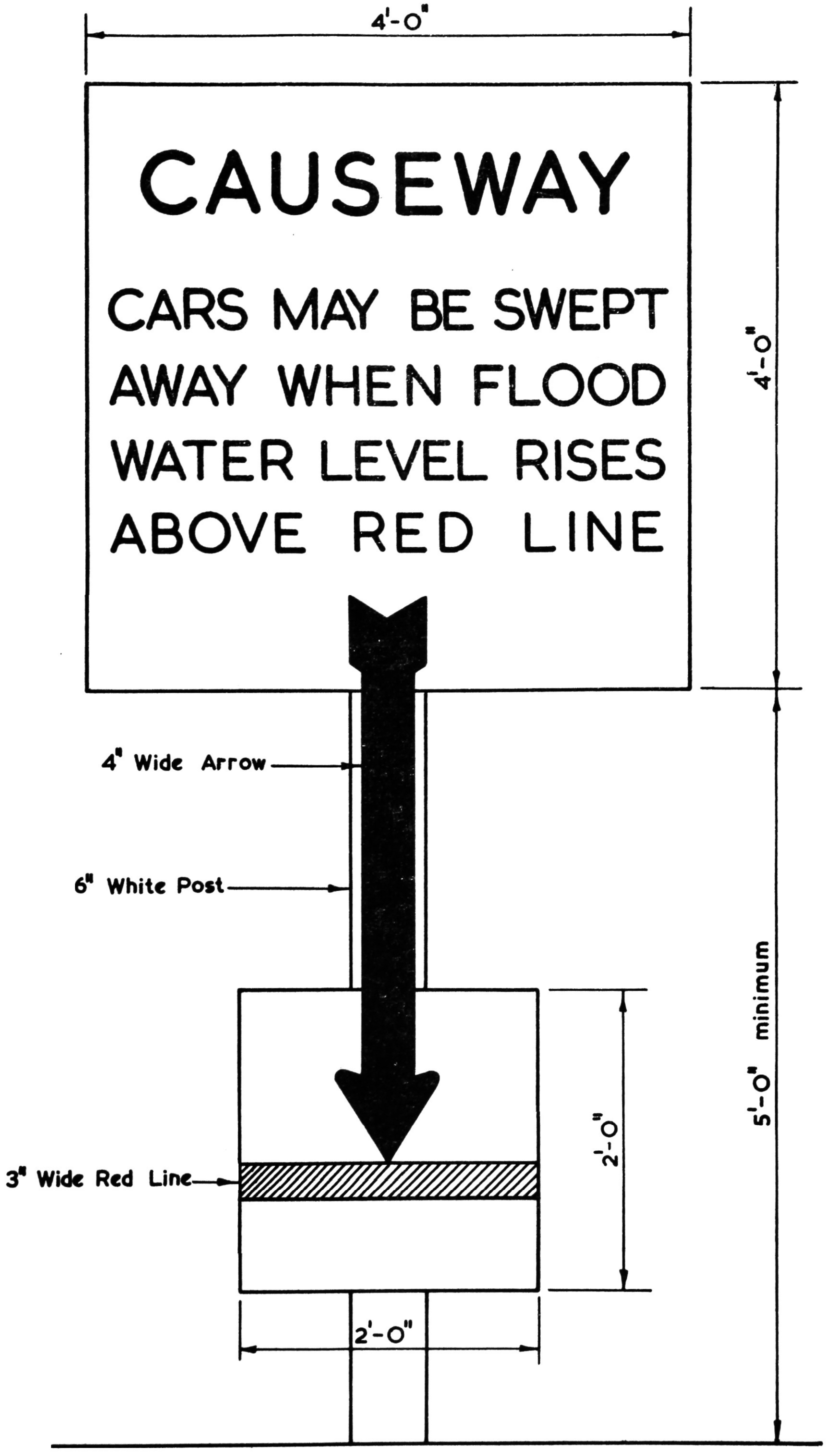


Fig. 21: Warning Indicator Notice.

recommended for use with the Warning Indicator Notice.

7.5 Causeways with Downstream Camber

Reference is made to Figures 5, 17, 18, 19 and 20. Causeways with downstream camber provide a maximum discharge of 4 cusecs per foot width and also the safe passage of cars provided the stream is not backed up to the extent that a hydraulic jump will occur on the causeway.

A hydraulic jump will not occur on the causeway if the difference in hydraulic energy level upstream and downstream of the causeway is greater than the difference in levelbetween the upstream and downstream edges of the carriageway slab of the causeway.

Thus if the crossfall amounts to 0.5 feet then the upstream energy level must be 0.5 above the downstream energy level.

Providing this difference in energy level can be certain, then the causeway with downstream camber is the best to use. If the causeway may drown out due to insufficient valley slope or downstream obstructions then a flat, or almost flat carriageway slab should be used.

7.6 Causeways with Subcritical Flow and Floodways

For causeways in coastal areas and elsewhere where the causeway is not more than two feet above the surrounding general ground level, and where the discharges will be drowned at all times, the top of the red line below the Warning Indicator Notice should be set 1.2 feet above the lowest level of the lowest causeway slab. This is represented by line AB in Fig. 5.

Floodways are a special case represented by point A in Fig. 5, and the Warning Indicator Notice should be headed FLOODWAY instead of CAUSEWAY.

7.7 Additional Notice for Heavy Cars

A supplementary small print notice could also be provided for the guidance of heavy cars as follows:-

"NOTICE FOR HEAVY CARS: Cars and other vehicles weighing in excess of 2,600 lbs. may be swept away when flood water level rises above the blue line. Heavy cars weighing more than 2,600 lbs. include Falcon, Holden, Valiant, Corona and large American cars." (See Fig. 22).

A thin blue line one inch wide would then be added 0.3 feet above the red line on the Warning Indicator Notice.

This small supplementary causeway notice would be about one foot square and would be placed at the end of the causeway immediately behind the end marker post or attached to the side of the end marker post. (See Fig. 24).

The total head of 1.5 feet would give a discharge of 5.7 cusecs per foot width. (See line DEF in Fig. 4).

7.8 Summary

Placing the red line below the Warning Indicator Notice at 1.2 feet gives excellent protection to cars on all recommended causeway sections.

Causeways with Upstream Camber are not recommended.

It could be argued that the safe level is set rather low, but the object is to give maximum protection to the public rather than to encourage them to take risks.

It should be remembered that the flood may be rising and the level may have risen several inches before the car reaches the other end of the causeway.

8. Causeway Design Recommendations

8.1 General Considerations

Fig. 18 is a perspective sketch of the proposed safe causeway. See also Photographs 1 and 5.

A suitable causeway location must be chosen by the engineer and orientated normal to the general direction of the flood plain. In alluvial country, a good location would be where the meander pattern of the stream bed is unlikely to cause future erosion against the upstream face of the causeway.

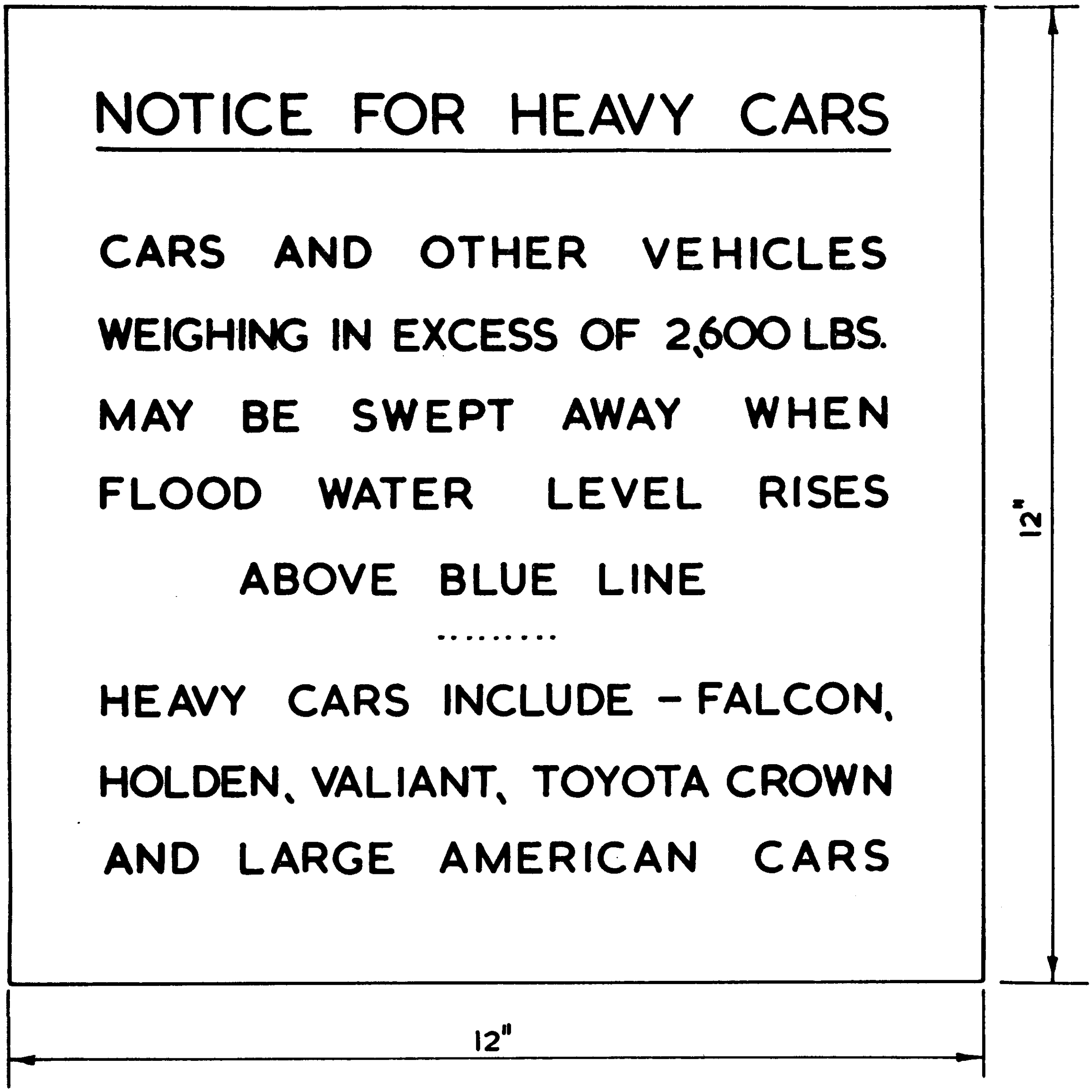


Fig. 22: Supplementary notice for heavy cars and vehicles.

4. Cars passing on model of recommended causeway.

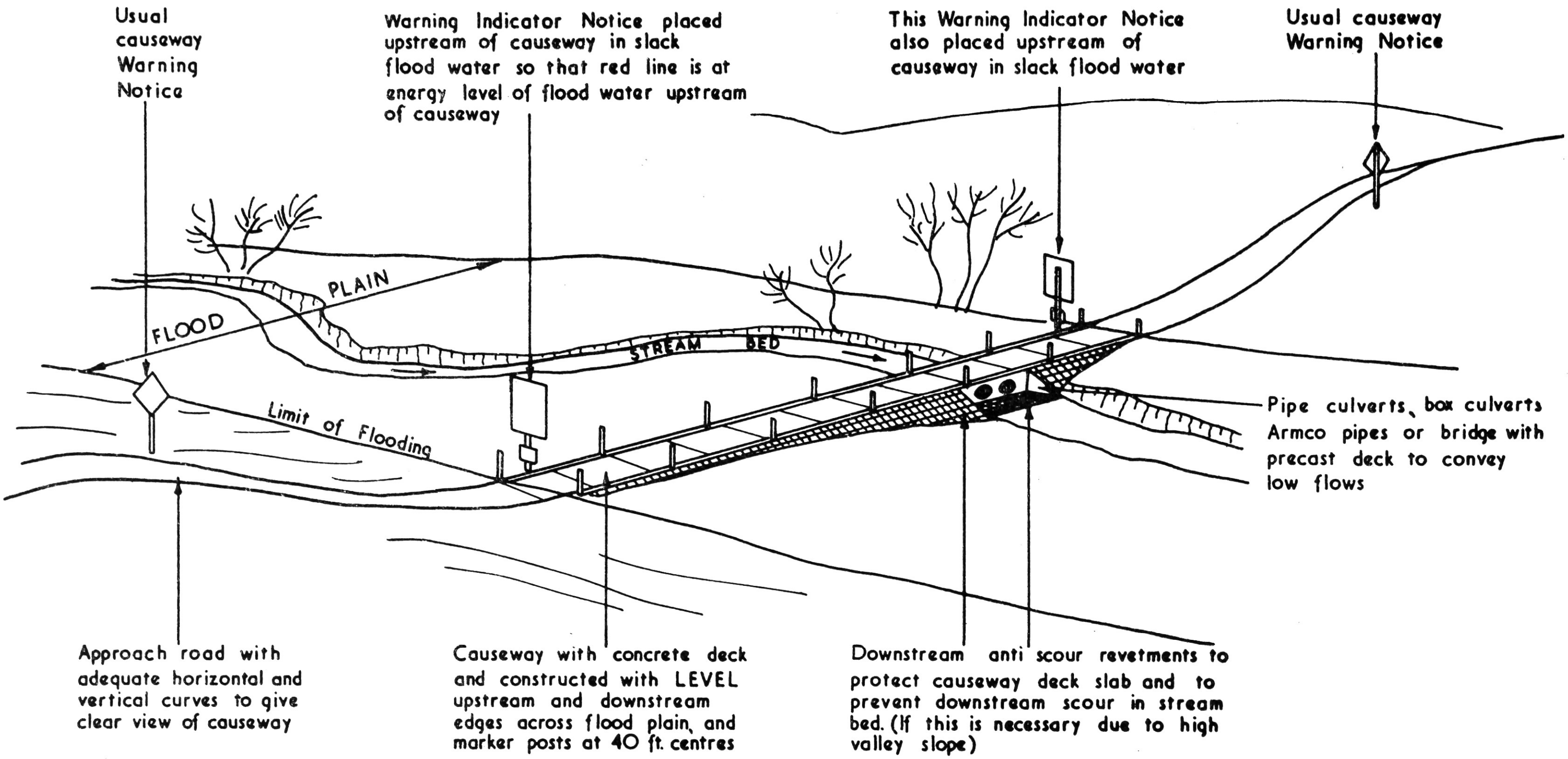


Fig. 23: Perspective sketch of proposed causeway.

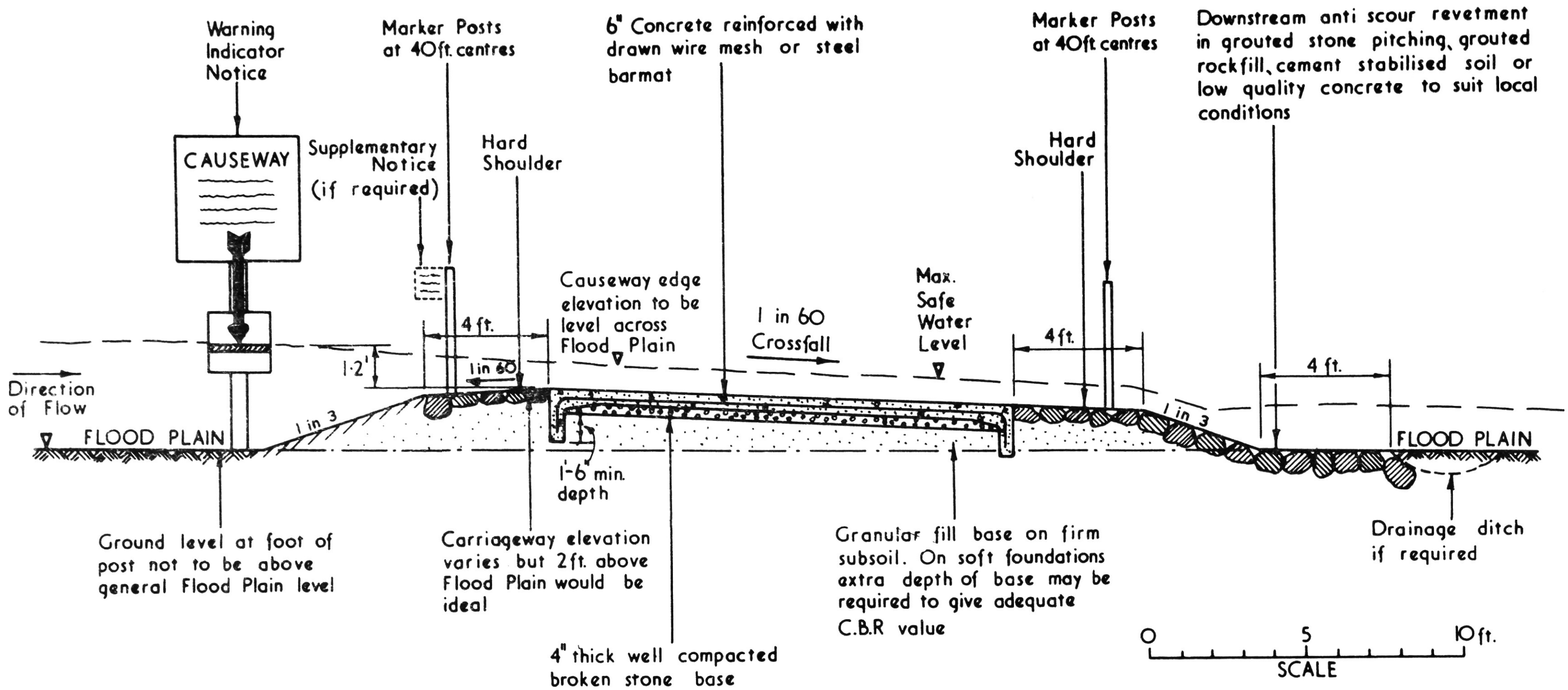


Fig. 24: Cross section of proposed causeway.

The design engineer must choose a causeway deck edge elevation which must be level across the flood plain. The height of the causeway will probably vary from zero at the edge of the flood plain to some 5 or 6 feet in the stream bed, to give sufficient height to construct a culvert designed to carry low flows. If there is no creek bed then a channel must be excavated for this purpose for a suitable distance upstream and downstream. The size of the culverts will vary according to the size and characteristics of the catchment. Where the causeway is in an area of low annual rainfall, the culvert could be as small as a 15 inch pipe sufficient only to drain the area immediately upstream of the causeway when floods are receding. Where the causeway is located in an area of high annual rainfall with a continuous water table in the catchment then a larger culvert must be used. The culvert should be capable of conveying the discharge for at least 98 pc. of the time and preferably 99 pc. of the time. The design engineer should estimate the cost of the causeway and culvert for various causeway elevations and arrive at the economic solution having regard for the tolerable frequency and duration of flooding and the number of vehicles per day using the road. Each road will have to be treated on its merits. It may prove economic to construct a very large culvert which will result in only very infrequent flooding of the causeway and thereby save the high cost of the anti-scour revetment over the length of the causeway. It is obviously better to eliminate causeways wherever possible in the interests of safety.

The causeway should also be located and orientated so that the approach roads will have adequate horizontal and vertical curves to give a clear view of the causeway.

The usual causeway warning notices should be located as recommended in the S. A. A. Road Signs Code and as shown in Figure 23.

8.2 Design Details

Figure 24 shows a cross section of a safe causeway. Details of causeway cross section design are given in Refs. 16 and 18. Some of these examples show upstream cambered causeways, but it is recommended that all causeways should be cambered downstream and the direction of camber should be ignored in Refs. 16 and 18. The cross-fall should be 1 in 60 or less where recommended in Section 7.

The causeway base should consist of suitable granular fill complying with a specification for granular filter blankets (see Ref. 30) and should be of sufficient depth and compacted strength to provide adequate bearing resistance for the road wheel loads having regard for the sub-soil strengths.

The carriageway should be of concrete slab construction to resist differential settlement due to subsoil movement. The slab thickness should be suitable for the class of road and reinforced if necessary. The edges of the carriageway should be level across the flood plain.

Marker posts 6 inches in diameter should be set at 40 ft. centres and set back from the carriageway a sufficient distance to prevent undue damage to the posts, say 3 feet. The hard shoulder should be 4 feet wide. The preferred side slope is 1 in 3.

The Warning Indicator Notice and Supplementary Notice for heavy cars should be positioned as shown in Figures 21 and 22 and as described in Section 7.

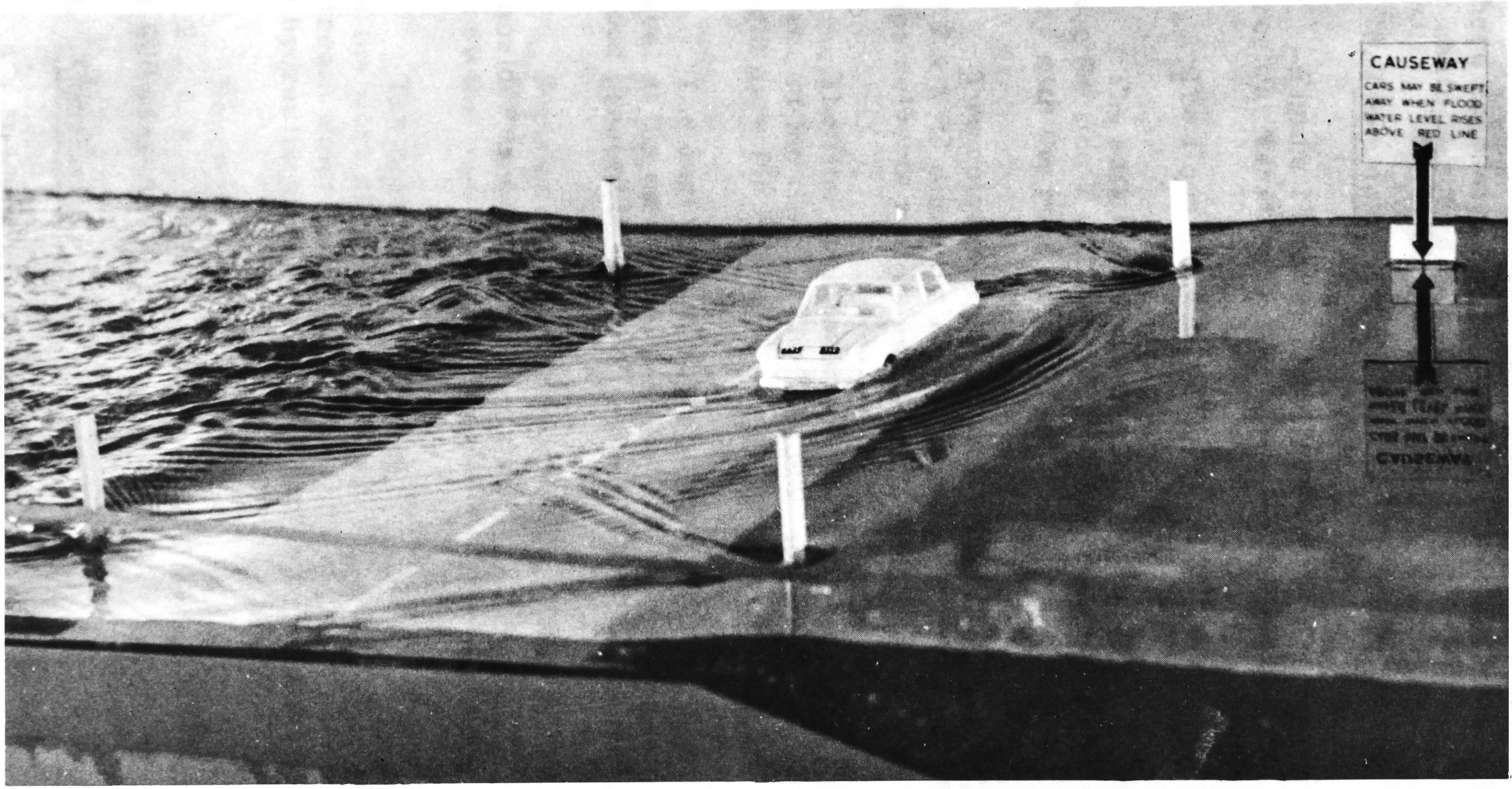
The hard shoulders and downstream revetment should be constructed in stone pitching, rock fill, stabilised soil or low quality concrete to suit local conditions. The toe of the downstream revetment should be sufficiently well constructed to resist piping due to subsoil movement in deep embankments.

In certain locations the revetments would be adequately protected if covered with grass turf and wire neeting. (Ref. 32).

The culvert to carry low flows may consist of pipe culverts, Armco pipes, box culverts or a bridge with a precast deck. A concrete headwall may be necessary.

The culverts may require antiscour revetments and wing wall revetments to prevent undermining of the structure by scour at this critical location (see Ref. 27).

A heavy wire rope or chain type guide rail could be provided, suspended at a height of say 3 feet between steel marker posts which would be used instead of the normal timber marker posts. Generally the wire rope would allow the unimpeded passage of flood waters but would hold back any car which tended to float away. In situations



5. Model of recommended causeway with downstream camber.

where excessive quantities of heavy debris are likely, use of the wire or chain is not recommended.

8.3 Example

Figure 25 shows the flow duration curve for Jerrabomberra Creek at Narabundah Lane near Canberra.

The flood plain is 1000 feet wide at a suitable location.

The safe discharge per foot width is 4 cubic feet per second; (see Section 7 and Fig. 5). Therefore the discharge over the causeway with the road still in use by all cars is 4,000 cubic feet per second.

Two culvert pipes would be provided in the stream bed consisting of 2 x 3 ft. diameter Armco pipes. The total discharge of the two pipe culverts will be some 100 cusecs before the causeway floods.

The flow duration curve shows that the causeway may flood for 2 pc. of the time. The flow over the causeway will be too deep for light cars for 0.005 pc. of the time.

The engineer must then establish the approximate flood water level at the causeway location for 4,000 cusecs. This can be done by flood gauging and the calculation of flood backwater curves.

Suppose the carriageway width is 20 feet and the downstream hard shoulder is 4 feet, totalling 24 feet. With downstream crossfall of 1 in 60 the total cross fall would amount of 0.4 feet.

The upstream water level at 4,000 cusecs after the completion of the work should therefore be at least 0.4 feet higher than the downstream water level calculated from the backwater curves, to prevent a hydraulic jump occurring on the causeway.

Hence the high upstream edge of the causeway should be set at 1.2 - 0.4 = 0.8 feet below the existing backwater level obtained for 4,000 cusecs.

9. Conclusions

9.1 Bridges are Preferable

The limiting safe depth on well designed causeways can be clearly defined for the wide range of cars in use to-day by means of clear and simple road traffic signs. Motorists often ignore notices so that wherever economically possible the very safest procedure is to eliminate the need for causeways by the construction of an adequate system of bridges and culverts.

9.2 Causeway Accidents

There are thousands of causeways in New South Wales and hundreds of accidents have occurred on them including many fatalities.

9.3 Tests with Model Car

Tests with a model Falcon car have shown the sideway force coefficient which must be developed between road surface and car tyres for a range of depths and velocities of flow on a causeway.

9.4 Road Friction Factor

A minimum sideway force coefficient has been adopted of $\mu = 0.3$. However, the safe value is uncertain. 0.3 was chosen as a lower limit of a number of possible values. It has been assumed that roadway surfaces are of concrete or equivalent material, normally dry for long periods and consequently unaffected by mosses, slimes, or like organic or inorganic accretions.

9.5 The Motor Car

The complete range of cars in use on the road has been examined, and the results obtained for the Falcon car have been applied to the whole range of cars by principles of similarity. The boundary curve represents a light car which is a true scale model of the Falcon, so that the analysis is reliable.

9.6 Tests with Model Causeways

Tests with model causeways show that the safest causeway has a downstream camber, provided that the difference in energy level upstream and downstream of the causeway is greater than the difference in level between the upstream and downstream edges of the carriageway slab. Where this difference in energy level is small or uncertain then a flat carriageway slab should be used.

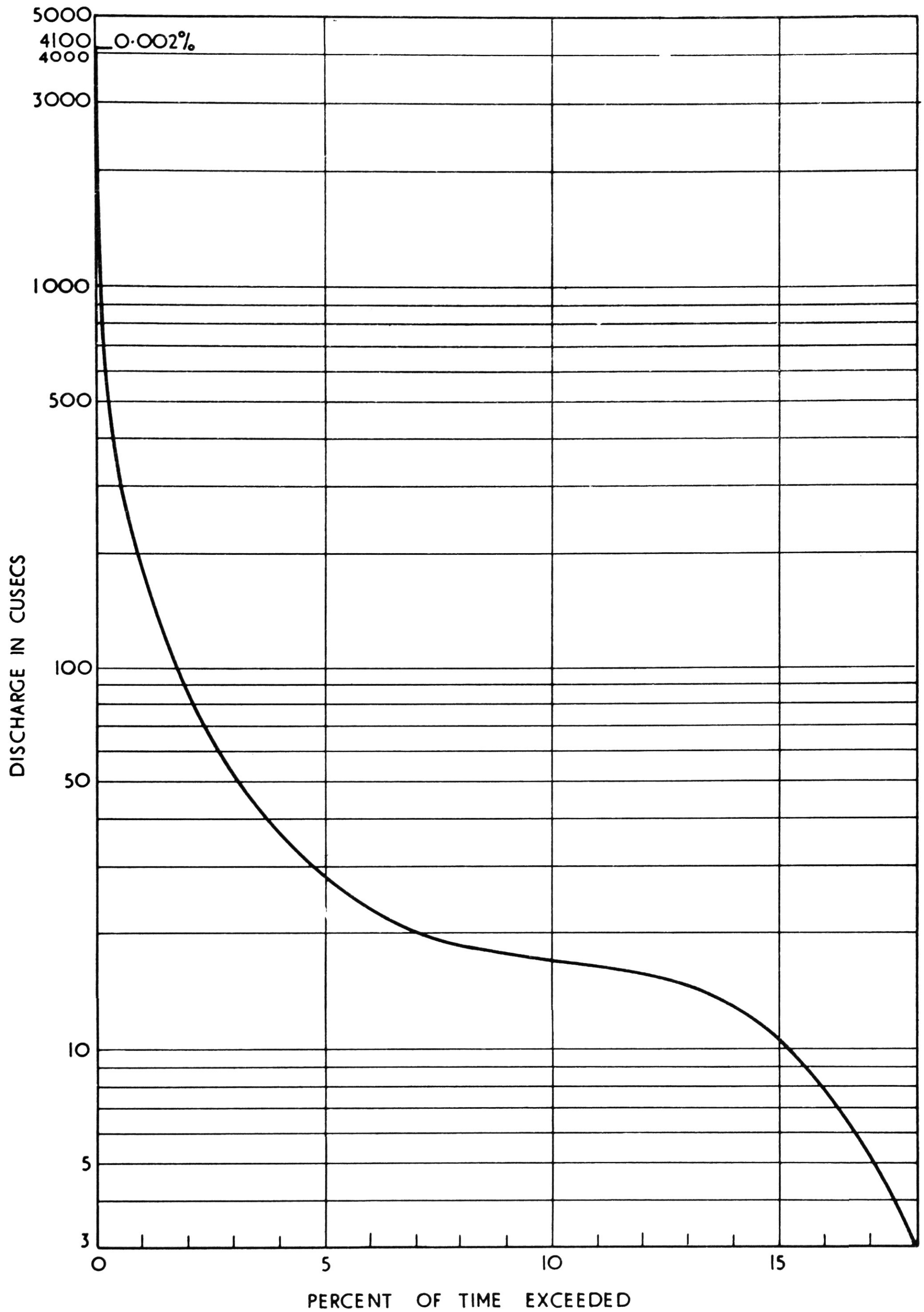


Fig. 25: Flow duration curve, Jerrabomberra Creek at Narrabundah Lane near Canberra.

9.7 Warning Indicator Notice

A warning indicator notice is proposed which is shown in Fig. 21. A supplementary small print notice can also be provided for the guidance of heavy cars.

9.8 Design Recommendations

The proposed safe causeway should have a concrete deck and should have level upstream and downstream edges across the flood plain. A perspective sketch and a typical cross section are shown in Figs. 23 and 24.

9.9 General Conclusion

The frictional resistance that can be developed between car tyres and carriageway surface is uncertain for the depths of water encountered on flooded causeways. However, the value selected should be reliable under flood conditions and for all carriageway surfaces.

The recommendations contained in this report are for the guidance of designers of low level causeways to suit Australian conditions.

The particular aspects of the report relate to the safety of motor vehicles on flooded crossings, the design of the causeway surfaces and the provision of warning notices.

The criteria contained herein, if adopted, will enable highway authorities to design safe causeways or alternatively these authorities will be able to clearly define the safe limits for the motorist by means of the proposed warning notices.

REFERENCES

1. Ewers, J. R. and Vallentine, H. R. "A Review of Literature on Causeway Design and Construction". Uni. N. S. W., W. R. L. 1962.

2. Bird, G. and Scott W. J. O. "Studies in Road Friction, I. Road Surface Resistance to Skidding". D. S. I. R., Road Research Tech. Pap. No. 1, H. M. S. O. 1936.

3. Bird, G. and Miller, R. A. "Studies in Road Friction, II an Analysis of the Factors Affecting Measurement". D. S. I. R., Road Research Tech. Pap. No. 2. H. M. S. O., 1937.

4. "Research on Road Safety". Chapter 14, Road Research Lab., Eng., H. M. S. O., 1963.

5. Horne, W. B. and Dreher, R. C. "Phenomena of Pneumatic Tyre Hydroplanning". N. A. S. A. Tech. Note 7ND-2056, Nov., 1963.

6. Horne, W. B. and Feland, T. J., "Influence of tyre tread pattern and runway surface conditions on braking friction and rolling resistance of a modern aircraft tyre." N. A. S. A., Tech. Note TN D1376, Sept., 1962.

7. Horne, W. B. and Joyner, N. T. "Pneumatic tyre hydroplanning and some effects on vehicle performance." S. A. E. Paper 970C.

8. Commonwealth Bureau of Census and Statistics. "Registrations of New Motor Vehicles - Make of Vehicle: Australia 1966." Canberra, Australia, S. B. 599.

9. The Editors Motor Manual, "Australian Used Car Market". Summer 1967, 30th Edition, 233 Collins St., Melbourne.

10. Motor, London, "Road Test Digests". Oct., Nov., Dec., 1966, Temple Press, 40 Bowling Green Lane, London E. C. 1.

11. Autorcar, London, "International Buyers Guide." 14th October, 1966.

12. Fry, A. S. and Hickox, G. H. "Calculating Flood Flow over an Embankment". Eng. News Record, Vol. 106, p. 557 Jan. - June, 1931.

13. Cupta, B. B. "Some Causeways on Sand Foundations Across Rivers in India and their Development to Submersible Bridges". J. Inst. Civ. Engrs. Vol. 33, No. 2, 144-152, Dec. 1949.

14. James, J. "The Grading of Causeways" Main Roads, Vol. 2, No. 2 18-30, Oct. 1930.

15. Lall, Y. K. "Some Causeways on Sandy Beds". J. Indian Roads Cong. Vol. 13 No. 3 347-375 Jan. 1949.

16. Leech, J. D. "The Building of the Main and Development Road System in W. A. 1926-1956". J. Inst. Eng. Aust., Vol. 28, No. 12, 317-326, Dec. 1956.

17. N. S. W. Dept. of Main Roads. "Instructions for the Design of Two-Lane Rural Highways" M. R. Form No. 355 - Road Design Standards 1937.

18. N. S. W. Dept. of Main Roads "Principles of Causeway Design" Main Roads Vol. 3, No. 9, 136-142, May 1932.

19. Raju, S. P. "Causeways or Submersible Bridges" Hydrabad Eng. Res. Lab. Annual Report, 1950, p. 45-60.

20. Symposium on the Darwin Overland Road. J. Inst. Eng. Aust. No. 7, 155-171, July 1941.

21. Woodburn, J. G. "Tests of Broadcrested Weirs" Trans. A. S. C. E Vol. 96, Paper No. 1797 p. 387-453 1932.

22. Yarnell, D. L. and Nagler, F. A. "Flow of Water over Railway and Highway Embankments" Public Roads Vol. 11, No. 2 30-34, April 1930.

23. Sherrard, H. M. "Australian Road Practice" Melb. Uni. Press 1958.

24. Standards Association of Australia. "Australian Standard Rules for the design, location, erection and use of road traffic signs and signals". Known as the "SAA Road Signs Code" No. C. E. 1 - 1960 Science House, 157 Gloucester St. Sydney.

25. S. A. A. "Australian Standard Specification for Road Signs". No. E. 36-1960, Sydney.

26. S. A. A. "Standard Alphabets for Road Signs". No. E. 37 - 1960, Sydney.

27. Vallentine, H. R. and Cornish, B. A.,. "Culverts with Outlet Scour Control" Report No. 62, Uni. N. S. W., W. R. L. March, 1962.

28. Dept. Public Works, "The Causeway Investigation, Interim Report", Hydraulic and Soils Laboratory, Manly Vale, N. S. W. Aug. 1961.

29. Souter Gavin, "The Car Makers (3)" Sydney Morning Herald, 14th June, 1967.

30. Posey, C. J. "Some Basic Requirements for Protection against Erosion", p. 85, Proc. Int. Assoc. Hyd. Res. Aug. 1953, Minneapolis, Minnesota.

31. Kindsvater, C. E., "Discharge Characteristics of Embankment-Shaped Weirs" Geol. Surv. Water Supply Paper 1617-A, U. S. Geol. Surv. 1964.

32. Yong, K. C. and Stone, D. M. "Resistance of Low Cost Surfaces for Farm Dam Spillways", Uni. N. S. W., W. R. L. Report No. 95, April 1967.