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NATIONAL RESEARCH COUNCIL

DIVISION OF BUILDING RESEARCH

# AN INVESTIGATION OF VIBRATIONS THROUGH SOIL CAUSED BY HEAVY VEHICLES IN WINNIPEG

by

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# PREFACE

The Division of Building Research of the National Research Council of Canada is naturally interested in unusual foundation problems which occur throughout the Dominion. In particular, foundation conditions in the main cities of the country will always be of special concern in view of their economic importance.

One of the many important problems encountered in foundation work is that related to the transmission of vibrations through soil. This is met with in connection with bases for reciprocating machinery and in blasting operations. More recently, the use of heavy vehicles on city streets has given rise to serious complaints arising from the induced vibrations and their passage through soil.

The Division looks forward to investigating this problem generally. It was therefore unusually interested in a request which came from Mr. W. D. Hurst, the City Engineer of Winnipeg, with regard to an acute problem of vibrations in his city which appeared to be related to the operation of trolley buses.

It was at once a privilege and a pleasure for the Division to co-operate with Mr. Hurst and the staff of the Winnipeg Electric Company Limited in making a study of the Winnipeg problem. The Division was fortunate in being able to arrange for Mr. H. B. Sutherland to conduct the necessary field and office investigations. Mr. Sutherland is a member of the Civil Engineering staff of the University of Glasgow who has now spent two periods working with the Division of Building Research.

This report presents a summary of Mr. Sutherland's investigations on the basis of which certain conclusions and recommendations are submitted. Since the report deals with a difficult local problem, it must be emphasized that no part of it must be reproduced in any form whatsoever. It represents a useful contribution to the more general problem and it is therefore hoped to publish, at a later date, those parts of the report which are of general interest.

1st October, 1949

R. F. Legget
Director

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## SUMMARY

This report describes a series of experiments conducted as a result of complaints received from property owners in the City of Winnipeg. These owners stated that, in some cases, damage had resulted to their property due to the vibrations resulting from trolley buses which have recently been introduced in the City. These vibrations were attributed to various different reasons such as speed and weight of the buses, thickness of road bed and condition of road surface. Methods are described whereby the effects of these various causes were separated, and recommendations are made for the reduction of the vibrations.

## INTRODUCTION

Since the introduction of trolley buses in Winnipeg, during the last few years, complaints of vibrations resulting from the buses frequently have been made. These complaints have been received by the Winnipeg Electric Company, who operate the vehicles, and by the City Engineer, who is responsible for the construction and maintenance of the roads and streets on which the vehicles run. Similar complaints, to a lesser extent, have also been made of gasoline buses.

Opinions have often been expressed, with little or no evidence to substantiate them, as to the primary causes of the vibrations and as to methods of controlling and minimizing them. There was therefore need for field research on this problem.

The Division of Building Research of the National Research Council of Canada is vitally concerned with problems and research in the fields of building and construction engineering. One particular branch of research which they wish to develop and in which little work has yet been done by any research institution, is that concerning the transmission of vibrations to structures from causes such as blasting, industrial machinery, pile driving, and heavy traffic. An investigation of vibrations from trolley buses can therefore, at the present time, be of service to the City of Winnipeg and can also be of use to the Research Council in the much wider sense of the general investigation of vibrations in structures.

Mr. W. D. Hurst, City Engineer of Winnipeg, was aware of the interest of the Council in vibration problems. Accordingly, it was arranged that the Council should conduct an investigation of the vibrations resulting from trolley buses with the collaboration of the interested authorities in the City of Winnipeg.

SOIL AND FOUNDATION CONDITIONS IN WINNIPEG

During the Pleistocene or Glacial Period, the area on which the City of Winnipeg stands was inundated by a vast body of water called Lake Agassiz. This water was retained by ice barriers and glacial deposits and during its existence, successive layers of sedimentary deposits were laid down on the Lake bottom. When these ice barriers retreated, the impounded water was released.

The City of Winnipeg is built upon these sedimentary lake deposits. The strata from prairie level to bed rock, which is a distance of 60 to 70 feet, is approximately as follows, progressing from the surface down:

(a) 2 feet of loam;
(b) 3 feet of silty clay;
(c) 4 feet of brown clay;
(d) an average of 12 to 18 inches of "yellow" clay;
(e) approximately 20 feet of dense chocolate-coloured clay;
(f) approximately 20 feet of dense blue clay;
(g) 2 feet of boulders and ground-up limestone;
(h) 2 feet of semi hard-pan;
(i) 5 to 10 feet of hard-pan;
(j) limestone bed rock.

The information given above was obtained from a report presented to the Executive Committee of the Winnipeg Branch of the Engineering Institute of Canada by the Committee on Foundations in August, 1937.

During dry seasons, the surface soil dries out by evaporation and the clay is broken up by shrinkage cracks. In semi-arid regions, such as western Texas, these cracks can occur to a depth of 20 feet and when rain falls, the cracks fill with water, the clay swells, and heaving of the ground surface occurs. This depth of drying out is not so great in the Winnipeg area, probably extending to just below the bottom of the "yellow" clay layer mentioned above. However, these Winnipeg top soils have a high shrinkage and expansion coefficient and considerable heaving of building occurs after a prolonged dry spell and the subsequent rain. In addition, a building acts as a "cover" on the clay and reduces the loss of water in the clay due to evaporation. Hence, the water content of the clay located beneath the "covered" areas, increases relative to the "uncovered" clay. A heave of the centre part of the "covered" area occurs with respect to the outer boundaries of the area. The amount of heave is probably independent of the weight of the building but its effect on the building is very similar to that of unequal settlements. It leads to cracked basement floors, basement walls, partition walls and outside walls.

The foundations of heavy buildings in Winnipeg are generally built on bed rock by means of caissons. Medium size buildings have, as their foundations, spread footings extending to the layers of chocolate or blue clay or these buildings may be carried on wooden or reinforced concrete piles driven to refusal at semi hard-pan. Foundations such as these described above are normally carried to depths unaffected by shrinkage with its resulting heaving action. This is not true of ordinary residential construction. With house construction, the foundation does not require to be greater than 4 feet 6 inches below grade level in order to conform with the Winnipeg Building Code. The depth of cracking is much greater than this. Thus the great majority of houses in Winnipeg are subjected to considerable differential movements in their foundations after extended dry periods.

These movements can be seen by examination of houses in practically any district of the City, irrespective of the location of the house with respect to heavy traffic. It is the exception rather than the rule to find a house in Winnipeg free from cracks. These cracks appear to have been caused by differential movements in the foundations.

## REVIEW OF PREVIOUS REPORTS ON VIBRATIONS IN WINNIPEG SOILS

(a) Mr. C. M. Hovey, of the University of Manitoba, on behalf of the Winnipeg Electric Company, made a detailed study and submitted a report entitled "Vibrations of Structures by Vehicular Traffic". This study extended over a period from June, 1945, to September, 1946, and the report is dated November 3rd, 1947. Two main points were investigated by Mr. Hovey:

- (i) The magnitude of vibrations induced;
- (ii) The effects of vibrations on the settlement of footings.

From his investigation, Mr. Hovey concluded that traffic vibrations are not an important factor in the settlement of footings or in producing vibrations of sufficient magnitude to cause structural damage.

(b) Mr. W. D. Hurst, City Engineer of Winnipeg, had some communications in late 1948 with the London (England) Passenger Transport Board, an organisation which includes the use of some 1760 trolley buses in its operations. The Board has experienced no trouble whatsoever from vibrations due to trolley buses. They suggested, however, that vibrations in Winnipeg were probably due to irregularities in the road surface. They were of the opinion that smaller or lighter vehicles, driven at lesser speeds, would not afford a solution to the problem. They suggested that digging a trench 8 feet deep and 2 feet wide alongside the road and filling it with sand would, perhaps, prove an effective screen against local earth-borne vibrations.

(c) During November, 1948, Mr. W. D. Hurst, on behalf of the City of Winnipeg, commissioned Dr. Frank Allen, Emeritus Professor of Physics at the University of Manitoba, to prepare a report on the soil vibrations occasioned by mass transportation and other vehicles. In his report and letter of transmittal dated January, 1949, Professor Allen made the following conclusions:

(i) Trolley and gasoline buses both set up greater vibrations than street cars. Greater vibrations should be experienced upon acceleration and lesser vibrations when the vehicle is decelerating;

(ii) On the basis of Mr. Hovey's report, Professor Allen stated the intensity of vibration is increased disproportionally by increased unevenness of the road surface;

(iii) On an experimental basis, a sand-filled trench similar to that proposed by the London Passenger Transport Board should be prepared as a possible means of dampening vibrations;

(iv) Doubt was expressed as to whether an increase of the thickness of the pavement from six inches to eight inches would have sufficient effect in reducing vibrations to negligible proportions but rather a much greater increase would be required, possibly up to 10 or 12 inches.

(v) Prevention of vibrations must be done in the buildings themselves, rather than in the streets or vehicular traffic;

(vi) With such information as is at present available, very little can be done to prevent the generation of vibrations in the streets unless at extremely great cost.

Comments on the various points made in the above reports will be made as a result of the tests described in this Report.

## COMPLAINTS FROM PROPERTY OWNERS

Complaints have been made to the Winnipeg Electric Company and to the City Engineer regarding the damage being caused to property by the vibrations produced by trolley buses and also, to a minor degree, by gasoline buses. These complaints have been fairly widespread throughout the City along the various trolley bus routes. The highest concentration of complaints came from the River Heights area from main trolley bus route. A number of the property owners in this area have grouped together and secured the legal advice of Mr. C. V. McArthur, a barrister in Winnipeg. Mr. McArthur convened a meeting of the complainants, which the writer attended, and from the ensuing discussion, the following points emerged:

(a) Before the introduction of trolley buses, street cars ran down the centre strip of Academy Road. This centre strip is approximately 21 feet wide. The construction and maintenance of the centre strip was the responsibility of the Winnipeg Electric Company while the street cars were in operation. To accommodate the ties and rails and provide a suitable base, a total thickness of approximately 24 inches of concrete was provided in the centre strip. Between this centre strip and the curbs on each side, the City of Winnipeg had provided a road approximately 10 inches thick. When the street cars stopped operating, the rails were removed and the complete width of carriage-way re-surfaced with asphalt. A cross section of the roadway is shown in Sheet 1, Figure 2.

(b) No undue earth-borne vibrations resulted from the street cars, though considerable nuisance resulted from air-borne vibrations or noise caused by these vehicles.

(c) Since the introduction of the trolley buses, considerable vibrations have been apparent in the property adjacent to Academy Road. It was claimed by the majority of the complainants that their property was being damaged by these vibrations, cracking and falling of plaster was reported in a number of cases. Cracking and fracture of basement walls and floors was reported in other cases. Damage to stucco facings was also the basis of some complaints. Some complainants stated that pictures on their walls moved, that crockery vibrated, and that the beds shook. Vibrations were worse upstairs than downstairs.

(d) Various reasons and conditions were put forward by the complainants as being responsible for the vibrations. These are listed as follows:

(i) The thickness of pavement between the old street car tracks and the curb was stated as being inadequate. Little or no vibrations were felt when the trolley buses ran on the centre strip, while considerable vibrations are experienced in the outer strips of lesser thickness. Some complainants stated that this outer strip was only two or three inches thick. It was suggested at the meeting, that these outer strips should be increased in thickness to make them more in accord with the road thickness existing in the centre strip.

(ii) Vibrations were more noticeable in winter when there were lumps of ice on the road surface. This problem is accentuated by the steam pipes from the district supply system. These pipes, in winter, impart heat to the road surface, melt snow, and produce irregularities in the road surface. Vehicles running over these irregularities produce considerable vibrations.

(iii) Complainants were contradictory in their evidence as to whether the vibrations were greater when the buses were accelerating or decelerating.

(iv) All were agreed that increase in speed brought increased vibrations. Excessive speeds were very noticeable early in the morning and late at night.

(v) Some relief from vibrations was provided when lighter vehicles were used.

## INSPECTION OF DAMAGE TO PROPERTY

As the result of the meeting with the property owners in the Academy Road area, a number of houses in that area were visited and inspected. These houses visited are situated directly on Academy Road or closely adjacent to it.

Practically all of these houses inspected showed signs of cracking in either the basement floors, partition walls, basement walls or outside walls. A number of the owners stated that these cracks existed in their houses before the trolley buses were introduced. Others stated that the cracks appeared after the introduction of the trolley buses. In some new houses that have been built since the trolley buses started operating, cracks have appeared and are attributed to the vibrations caused by the trolley buses.

In one house which the present owner has occupied for about one year, slight plaster cracks were attributed to vibrations. Inspection of the house showed fairly extensive cracking in the basement walls which had been repaired by the previous owner before the trolley buses were operating.

Houses in the same Academy Road area, well removed from heavy traffic such as trolley buses, showed similar signs of cracking, sometimes much worse than those houses more close to the bus route.

As a result of the inspection, the following conclusions may be reached:

(a) The vibrations, apart from any structural damage they may be causing, constitute a definite nuisance, depending on the susceptibility of the person. The physiological significance of vibrations on human beings will be discussed later in this report;

(b) Most houses inspected showed cracking. Contradictory opinions were expressed by property owners as to the cause of these cracks. While it is almost impossible by visual inspection to categorically state that the cracks are due to vibrations or heaving of the foundations, the cracks were characteristic of the form of deformation produced in a building by the latter cause.

## FACTORS AFFECTING VIBRATIONS

The various factors affecting vibrations may be listed as follows:

(a) Weight of vehicle;
(b) Speed of vehicle;
(c) Braking and acceleration characteristics of vehicle;
(d) Condition of road surface, that is, whether bumpy or smooth;
(e) Construction of road bed, that is, thickness and composition;
(f) Nature of soil conditions;
(g) Distance of vehicle from affected structure.

Some of these factors are of greater concern to the interested authorities than others and the results of any investigation should differentiate between these various factors.

The Winnipeg Electric Company kindly gave the use of two vehicles with which to conduct the tests. The first was a Brill Trolley Bus, No. 1682, of the type regularly in use. Complaints have been made of the vibrations caused by this vehicle. This trolley bus, of unloaded weight, 18,510 lb., was loaded with sand bags to bring it up to a total vehicle and passenger load of 25,000 lb. The bus is shown in Figure 8, Sheet 4. The second vehicle was a gasoline bus of a type used in other transport routes operated by the Company. The test weight of this vehicle was approximately 15,000 lb. The operation of these two vehicles, at controlled speeds and under conditions of braking and acceleration, enabled control to be exercised over factors (a), (b), and (c).

In the note on Complaints from Property Owners it was stated that vibrations were worst in the winter when irregularities were formed on the road surface by ice. In July, when the investigations described in this Report were conducted, there were few bumps or pot holes in Academy Road. There were thus few opportunities of observing vehicles haphazardly hitting bumps and, in any case, their speeds would have to be estimated. To simulate the shocks to which the vehicles are subject in winter, a series of ramps were constructed as shown in Figure 3 of Sheet 1. These ramps, 1 1/8", 2 1/16", and 3 1/16" high, afforded an opportunity of observing the relative effect of such bumps and the intensity of vibrations produced. Control could thus be exercised over factor (d).

As previously described, and as shown in Figure 2 of Sheet 1, Academy Road has two road bed constructions, an approximately 24-inch thickness in the centre strip and a 10-inch construction in the outer strips. Running the vehicles on these various tracks gives control over factor (e).

The vehicle tests were conducted at the same location and thus any variation in intensity of vibrations which may be due to variation in soil conditions did not occur in these tests. Factor (f) was therefore of no account.

The distance of the centre and outer strips from the observation point varied from 25 feet to 60 feet. These small differences of distance are not sufficient to produce any great change of vibrations over them. This is shown by the slight differences obtained in the measurements of the vibrations.

## OBSERVATION STATION

Dr. J. P. Beattie, who owns a house on the north-east junction of Academy Road and Queenston Street at 435 Academy Road, kindly gave the use of his house as an observation station. The house was ideally located for the purpose. Its position is shown in plan in Figure 1 of Sheet 1, and a view of the house is shown in Figure 6, Sheet 3. The main observation point was downstairs, the seismograph being set up close to window 1 in Figure 3. The remote control switch was operated from outside this window. A second observation point upstairs was established close to window 2. All the recordings, apart from two, were taken at these two observation points in Dr. Beattie's house. The other two recordings were taken in a house close to Academy Road.

## TEST PROCEDURE

For purposes of testing, Academy Road was divided into four strips, as shown in Figure 2, Sheet 1. The strips were described as follows:

(i) Outer strip, near side;
(ii) Centre strip, near side;
(iii) Centre strip, far side;
(iv) Outer strip, far side.

The following tests were run:

Using the Brill Trolley Bus 1682:

(a) In each of the four strips, with and without the various ramps, two complete sets of tests were run over a range of speeds from 10 m.p.h. to 40 m.p.h. The observation point was downstairs in Dr. Beattie's.

(b) In the outer strip, near side, with and without the various ramps, tests were run over a range of speeds from 10 m.p.h. to 40 m.p.h. to test the braking and acceleration characteristics. The observation point was upstairs in Dr. Beattie's.

Using the Gasoline Bus:

(a) In the outer strip, near side, with and without the various ramps, tests were run over a range of speeds from 10 m.p.h. to 40 m.p.h. The observation point was downstairs in Dr. Beattie's.

In addition, both upstairs and downstars in Dr. Beattie's and at one other location, records were taken of the vibrations produced by jumping on the floor.

## RECORDING APPARATUS

The instrument used for measuring the vibrations was the Leet Seismograph. This seismograph was designed and constructed primarily for the registration of vibrations from traffic, dynamic blasts, machinery, and general industrial sources. It measures the longitudinal, vertical, and transverse components of vibrations. For vibrations of frequency greater than three cycles per second, it gives a record directly proportional to displacement.

The instrument is essentially a mechanical-optical system magnetically damped. The inertia elements are suspended by flat springs and have mirrors attached to them. Beams of light are focussed on these mirrors and in turn are directed to a moving roll of recording film. The movement of the mirrors, due to the vibrations, produces a corresponding movement of the light beam on the film, and a record of the three components of vibration is obtained when the film is developed. This record has a magnification factor of 50 and registers displacements of from about 0.002 inches to 0.18 inches. The instrument can be operated by a remote control switch. The seismograph is shown in Figure 4 on Sheet 2. Figure 5, on the same sheet, shows the instrument being operated using the remote control switch. Typical records from the seismograph are shown on Sheet 5. These records have been reduced to about one half their normal size.

## RESULTS

The motion caused by vibrations is called Harmonic Motion. A study of the fundamentals of harmonic motion shows that the important factors are the amplitude of the wave and its frequency, which is the number of complete waves transmitted in one second. The amplitude is a measure of the actual displacement due to the wave action. The acceleration and velocity of motion can be calculated, knowing the amplitude and frequency. From the amplitude, acceleration, and velocity, the energy transmitted by a wave can be calculated.

Various quantities have been used to measure the intensity of vibrations. Earthquakes are sometimes classified by their acceleration. However, the accelerations produced by earthquakes are extremely low and much less than the acceleration of gravity. Earthquakes have a low frequency which gives each wave a comparatively long period of duration and so allows a large transmission of energy. When vibrations are measured in buildings, the accelerations produced are usually found to be high, occasionally higher than gravity and thus much higher than those from earthquakes.

The energy transmitted is low, however, since the frequency is high. The only absolute measure of intensity of vibrations, therefore, is by the measurement of the energy transmitted. Energy is inversely proportional to the square of the frequency.

However, for one particular problem where frequencies are of the same order, one factor may be used as a measure of vibration. This is done with earthquakes, and has also been done by the U. S. Bureau of Mines in their Bulletin No. 442, dealing with the Seismic Effects of Quarry Blasting. The damage acceleration relationship developed in this Bulletin is used as a measure of vibrations in the present Report. At the end of this Report, measurements of the amplitude and frequency of the vibrations recorded in the tests are tabulated. These can best be examined and interpreted from graphs of amplitude against speed for the conditions of different ramps and different running strips for the vehicles. A series of these graphs is also included in this Report.

From the tabulated results it can be seen that vibrations are transmitted through the Winnipeg soil at approximately 7.5 cycles per second. The natural frequency of Dr. Beattie's house and similar structures will be less than 2 cycles per second. Therefore, there is no possibility of a resonant condition, with its amplification of amplitude, arising due to coincidence of the applied frequency and the natural frequency. In any case, the development of resonance requires the application of more than one blow.

The frequency of the Winnipeg soil is very low compared with other soils, as can be seen from Table I.

Table I

| Soil | Frequency cycles per second |
|---|---|
| Waterlogged estuarine silt | 10 |
| Very light soft clay | 12 |
| Light waterlogged sand | 15 |
| Medium sand | 15 |
| Loose fill | 19.1 |
| Limestone | 30 |

The low frequency of the Winnipeg soil means that there will be a much higher transmission of energy through it than is usually experienced with soils. This, to some extent, accounts for the complaints of vibrations from heavy traffic in Winnipeg.

## THE RELATIVE EFFECT OF COMPONENTS OF VIBRATIONS

Sheets 14 and 15 give a comparison of the three components of the vibrations as the Brill trolley bus ran over various ramps placed in the outer strip, near side. These sheets show that, when observing downstairs, the vertical component is greatest, the longitudinal next, and the transverse least. Record No. 1 on Sheet 5 also shows this condition clearly. Accordingly, since the vertical component of vibration is greatest and the frequency of vibration is approximately the same in all cases, this component has been used as the basis of comparison between all tests where observations were made downstairs.

When the tests were conducted upstairs in Dr. Beattie's, it was seen that, while the vertical and transverse components were approximately the same as those obtained from similar tests observed from downstairs, the longitudinal component had increased to a large extent to become the strongest component. This, no doubt, is the reason for the complaints that vibrations are much more severe upstairs than downstairs. This increase is probably due to the lack of lateral stiffening in the frames of the buildings, so giving little resistance to the thrust of the longitudinal component.

We can now consider the various factors affecting the vibrations in the light of the test results.

### (a) Effect of Weight of Vehicles

Sheets 11 and 12 give a comparison between the vertical components of vibrations resulting from the Brill trolley bus 1682, weighing approximately 25,000 lb., and a gasoline bus, weighing approximately 15,000 lb.

With no ramp on the roadway, the amplitudes obtained are approximately the same for each vehicle. When ramps are introduced, differences in the amplitudes become apparent and the differences become more pronounced as the ramps increase in size. For a 3 1/16" ramp, the amplitudes from the gasoline bus are approximately one half those obtained from the Brill trolley bus. The curves for the two vehicles are of different form. This may be due to different springing characteristics of the vehicles.

It can be concluded that where irregularities exist in the road surface lighter vehicles produce less vibrations.

(b) Effect of Speed of Vehicle

When investigating the effect of speed on intensity of vibrations, the vehicles approached the observation point at the required speed and passed that point neither braking nor accelerating.

Sheets 6 and 7 give graphs of amplitude of vertical vibration against speed of vehicle. Where there are no ramps on the roadway, the amplitude appears to increase proportionally to the speed. Thus, for a normal roadway without ruts or undue irregularities, vibrations appear to be proportional to the speed of the vehicle. When ramps are introduced to the roadway, the general trend of the curves obtained is for increase of amplitude of vertical vibration with speed. However, there are variations or waviness within the curves. The cause of this waviness will be discussed when the effect of ramps on the roadway is dealt with.

(c) Effect of Braking and Acceleration

In the Braking Tests that were run on the Brill trolley bus, the procedure was to approach the ramp at a controlled speed and apply the total braking capacity of the vehicle when the rear wheels were just hitting the ramp. This is a much more severe case than that normally encountered in the daily operation of the buses. The tests were run with the 3 1/16" ramp on the outer strip, near side, the observations being taken downstairs in Dr. Beattie's. With the higher speeds, the braking effects on the trolley bus were becoming too severe and were discontinued. Sufficient data was obtained, as shown in Sheet 9, to indicate that the vibration effects, due to braking, are in no way as severe as those resulting from free uniform speed running. By applying the total braking, the trolley bus could be decelerated from 40 m.p.h. in a distance of 109 feet, at a deceleration of 10.8 m.p.h. per second, which is very severe.

An acceleration test, conducted when the trolley bus was passing over the 3 1/16" ramp at 30 m.p.h. and accelerating fully at 3.5 m.p.h. per second, gave vibrations much less than those resulting from the free running uniform speed condition.

(d) Effect of Ramps on the Roadway

As discussed previously, these ramps were introduced on the roadway to simulate the irregularities which occur in the road surface in winter time. The ramps were held in position by sand bags placed at either end and, if necessary, sand packing was put under the ramps to give them uniform bearing on the road surface. Sheets 6 and 7 show the comparison of the vertical components of vibrations arising from the use of the various ramps in the different running strips. These graphs clearly show that for all running strips, the vibrations are greatly influenced by the ramp used. As the ramps increase in height, the vibrations increase in intensity. This indicated that an uneven road surface with irregularities due to frost heaving, ice, badly-set manhole covers, or pot holes will develop vibrations greater than those arising from running on a smooth road surface.

As mentioned when discussing the effect of speed of vehicle, there is a waviness in the curves of amplitude against speed when ramps are introduced. A possible explanation for this waviness is as follows: it was noticed during tests in the speed range of 15 to 20 miles an hour that, as the bus passed over the ramps, its whole bearing weight was violently accelerated downwards. This seemed to be caused by the spring arrangement of the vehicle. As the speed increased beyond 20 miles an hour and particularly in the higher range 30 to 40 miles an hour, the bus, as it passed over the ramps, seemed to be "lifting off" its springs as if soaring. The acceleration downwards did not seem to be as great as for the lower speeds. Since the vertical force transmitted to the ground is a function of the acceleration of the vehicle, different vertical accelerations will produce different transmissions of energy to the ground and will thus affect the amplitude of the vibrations. Approximately 20 miles an hour appears to be a critical speed for the springing of the Brill trolley bus. To confirm this definitely, an extensive series of controlled tests would have to be conducted.

With the gasoline bus, increasing the ramp height produces a lesser increase of vibration than with the Brill trolley bus. This may be due to the two vehicles having different springing arrangements. A detailed analysis of the springing of these vehicles, however, would have to be conducted by a mechanical engineer.

(e) <u>Effect of Construction of Roadbed</u>

As discussed earlier, the centre strip of Academy Road has a 24-inch total thickness, while the outer strips have a total thickness of 10 inches.

Sheets 8 and 9 show the vibrations produced by the Brill trolley bus running in the various strips over the different ramps.

Generally, the vibrations produced in the outer strip, near side, that is, the strip closest to the observation point, are worst. This strip is 10 inches thick. There are no great differences between the vibrations from the other strips. If anything, the vibrations from the 24-inch thickness are slightly less than those from the outer strips, but all the strips are at slightly different distances from the observation point and the differences obtained may be due to these varying distances.

The conclusion can be drawn that slightly less vibrations result from a greater thickness of roadbed.

## RELATIVE EFFECT OF THE VARIOUS FACTORS PRODUCING VIBRATIONS

For any one vehicle it has been shown that speed, braking, acceleration, irregularity of road surface, and construction of road bed all have an effect on the intensity of vibrations produced. The comparative effect of these various influences can be determined from a plot of the envelopes of influence of the various ramps as shown in Sheet 10. In this diagram, envelopes have been drawn around all the plots of vertical components of vibrations due to different speeds, different running tracks, and different thicknesses of roadway.

From these envelopes it can be clearly seen that the most important factor affecting the vibrations (produced by the Brill trolley bus) is irregularity of the road surface. If bumps or depressions can be eliminated and the road surface kept smooth, the vibrations resulting are so low that they fall into the zones of not perceptible or only slightly perceptible in Sheet 16, which is a graph of the sensitivity of humans to vibrations.

## SENSITIVITY OF HUMANS TO VIBRATIONS

In 1931, at the Technical University of Stuttgart, Germany, H. Reiher and F. J. Meister conducted an extensive research on the sensitivity and response of humans to vibrations. In this investigation, a number of people were subjected to vibrations of various ranges of amplitude and frequency and their reactions recorded. A number of graphs were plotted showing the reactions and sensitivity of these people to vibrations for different positions of their bodies. Figure 16 is a reproduction of one of these graphs. It deals with the reaction of people, when standing, to the vertical components of vibrations. The authors, in their other graphs, show the reactions of humans to vertical components when lying down, to horizontal components when standing, lying down parallel to them, and lying down at right angles to them. When the subjects were standing, they were much more sensitive to vertical than horizon vibrations. When lying down, the vertical vibrations were not as noticeable as the horizontal. Horizontal vibrations were most disturbing when the subject was lying at right angles to the direction of the vibration.

Some of the subjects were much more susceptible than others. One woman had violent reactions when other people did not suffer appreciably.

The conclusions reached by Messrs. Reiher and Meister give an explanation of the complaints that property owners are disturbed by vibrations while lying in bed, especially where the bedrooms are upstairs. As was seen from the records, the longitudinal horizontal component of vibration is the greatest component upstairs. Thus, the most discomforting vibrations experienced in a house will be in bed upstairs when the bed is lying parallel to the direction of the vehicle causing the vibrations. If beds are placed at right angles to the direction of traffic, the vibrations will have a less disturbing effect on people.

Considering the vibrations produced in the tests described in this Report, the most severe vibrations come into Zone 4, on Sheet 16, that is, strongly perceptible. Under normal running conditions of the trolley buses, no vibrations as severe as this would be experienced.

Lines A and B have been superimposed on Reiher's and Meister's graph on Sheet 16. These lines have been taken from the U. S. Bureau of Mines Bulletin No. 442 (1942). In this report, entitled "Seismic Effects of Quarry Blasting", zones of damage due to vibrations are determined. Line A, which represents an acceleration of one tenth that of gravity, indicates the caution stage. Between lines A and B, there is likely to be some plaster damage due to vibrations. Beyond line B, which represents an acceleration of g, that of gravity, some structural damage will result. Acceleration cannot always be taken as a comparison of damage likely to be caused by vibrations, since energy transmitted should be the sole criterior of judgment. However, for specific conditions, e.g. earthquakes, or for similar types of structures, standards of intensity, based on acceleration alone, can be set up.

The Bureau of Mine's lines A and B can therefore be adopted in this Report as a basis of comparison since they were determined for similar types of buildings to those with which this Report is concerned.

## DAMAGE TO STRUCTURES FROM VIBRATIONS FROM HEAVY VEHICLES

The question arises as to whether the vibrations produced by heavy vehicles in Winnipeg in general and the trolley buses in particular are detrimental to structures.

A decision can be made from the vibrations observed, the research of Messrs. Reiher and Meister, and the investigations carried out by the U. S. Bureau of Mines. From Sheet 16, it can be seen that people are aware of vibrations long before there is any possibility of damage to the structure. Vibrations which would cause extreme discomfort to a person still would barely cause plaster damage to the house.

The vibrations produced during the tests conducted in Academy Road were more severe than any likely to be encountered in the normal operation of the vehicles under any conditions, during any season of the year. No vehicle would withstand the regular jars and jolts produced when driving at high speed over the ramps, and could not be economically operated under such conditions. Even so, the worst effect produced in the tests, 0.003 inches at 8.2 cycles per second, is a vibration strongly perceptible to humans but not damaging to structures.

Therefore it can be concluded that the vibrations from heavy vehicles in Winnipeg do not produce harmful effects on the structures.

## JUMPING ON FLOORS

Complaints of particularly severe vibrations were received from the wife of the owner of the house at 151 Montrose Street. This is the second house from Academy Road, proceeding northwards and is approximately 90 feet from Academy Road. The Brill trolley bus was run at 40 m.p.h. over the 3 1/16" ramp and vibrations recorded. These are shown on Record 3 of Sheet 5. The observation point was in a room above the garage. The vibrations measured were not as bad as those taken upstairs in Dr. Beattie's, but in this case also, the longitudinal component of the vibrations was greatest, indicating lack of lateral stiffening in the building.

As a comparison, records were taken with the instrument located in the same position in 151 Montrose Street of a man jumping on the floor. This record is shown in Record 4 on Sheet 5. Amplitudes of all the components of vibration in Record 4 are much greater than those produced by the trolley bus. Jumping on the floor, however, produces much higher frequencies. These are in the region of 50 cycles per second compared with those from the trolley bus which were transmitted through the soil at approximately 7.5 cycles per second. The energy transmitted in the first case is low, even though the amplitudes and frequencies are high. The high amplitudes obtained from jumping on the floor would, therefore, be more liable to produce plaster cracking than the vibrations from the trolley buses.

Jumping tests were carried out upstairs and downstairs in Dr. Beattie's. These are recorded as tests 181, 182, 183, and 184 in the Table of Results. The vibrations produced downstairs were greater than those upstairs, but in both cases, the vertical component was strongest while the longitudinal and transverse horizontal components were approximately equal. This differs from the upstairs observations of the trolley bus vibrations where the longitudinal component was much greater than the other two components. This indicates the need for lateral stiffening in the house.

## CONCLUSIONS AND RECOMMENDATIONS

(1) The frequency at which vibrations are transmitted through the Winnipeg soil is low compared to other soils. This means that there will be a much higher transmission of energy from the passage of vehicles than is usual. Greater energy means much more noticeable vibrations, the condition which exists in Winnipeg.

(2) It is the opinion of the writer that damage in the houses inspected, damage attributed to vibrations from trolley buses, was due to deformations produced by heaving or settlement of the foundations.

(3) The tests conducted produced more severe vibrations than will occur in normal operation of the buses. The worst vibrations produced in the tests were not sufficiently strong to cause any structural damage to buildings. These vibrations would not increase existing deformation due to other causes, unless complete support was removed from under the foundations of a building, a condition which has sometimes arisen after extended dry spells in Winnipeg.

(4) It has been suggested that the repetition of vibrations from the trolley buses will have a fatigue effect on the houses and so produce failure after a period of time. The writer does not believe that this condition will arise as neither the amplitudes of the vibrations nor the number of repetitions of stressing during the lifetime of a house are sufficiently large.

(5) Human beings are extremely sensitive to vibrations. They are conscious of vibrations which are about one hundredth of those which will cause only slight damage to structures. Vibrations, which cause no structural damage, can have a definite nuisance value. The nuisance can be accentuated by loose fittings in the houses which rattle at a slight vibration. A suggestion has been made in this Report for the reduction of the effect of vibrations in upstairs bedrooms by placing furniture with respect to the direction of vibration origin.

(6) Any steps which can reasonably be taken, should be taken to alleviate the nuisance value of the vibrations. Considering the trolley buses, examination of the various factors producing the vibrations showed that the most important one was the effect of the ramps on the roadway. If a smooth surface can be maintained on the road, very little vibration will result within the speed range of the trolley bus.

Various factors, however, prevent the maintenance of smooth road surfaces in Winnipeg.

The underlying soil consists, in some places, of material which is highly susceptible to frost heaving, in other places, of material which varies greatly in volume with change of water content. District heating mains cause irregularities in the road surface in winter. Manholes are apparently subject to heaves which leave their covers above the street level. Boulevard trees attract water from underneath the roadway. This can lead to settlement of the roadway. In summer, due to the heat, creep of the asphalt occurs which can give a washboard effect in the roads.

The points outlined in the preceding paragraph indicate the difficulty of maintaining a smooth surface on the roadways in winter in Winnipeg.

The use of lighter vehicles will reduce the vibrations. This is shown by the tests with the gasoline bus. The worst vibrations produced by the gasoline bus fall into the zone of "distinctly perceptible" in Sheet 16.

This zone of vibration still would constitute a nuisance though a lesser one than would the trolley buses.

(7) The difference in amplitudes obtained from the trolley bus and gasoline bus may not be due to weight alone. The curves obtained from the two vehicles suggest different springing characteristics. These should be investigated by a qualified mechanical engineer.

(8) It is recommended that some of the tests described in this Report be repeated in winter when the soil is frozen in order to investigate the relative effects of frozen and unfrozen soil.

(9) Lack of stiffness against lateral movements has been shown to exist in houses. This is indicated by accentuated horizontal displacements upstairs compared with those downstairs. In any new houses or structures to be built close to heavy traffic routes, consideration should be given to the provision of additional stiffening or the placing of spring-padding of materials such as cork or asbestos fibre to reduce the effect of vibrations.

Commenting on suggestions made in previous reports on the vibrations in Winnipeg, it can be seen from the tests conducted that

(1) The greatest vibrations are obtained when the trolley bus is running at a uniform speed and not when it is braking or accelerating;

(2) Increasing the pavement thickness to 10 to 12 inches would not appreciably reduce the vibrations.

Sand-filled trenches would be an expensive installation and their success, judging by similar experiments with foundations for steam hammers, would be extremely doubtful. They are definitely not recommended by some authorities.

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# TABLES OF RESULTS

Vehicle: Brill Trolley Bus No. 1682

Observation Point Downstairs in Dr. Beattie's House
Vehicle Running Track Outer Strip Near Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. Vert. Comp. c.p.s. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | - | .0001 | - | - | None | 10 | |
| 2 | - | .0001 | - | - | do. | 10 | |
| 3 | .0001 | .0002 | .0001 | - | do. | 16 | |
| 4 | .0001 | .0003 | .0001 | 7.6 | do. | 22 | |
| 5 | .0003 | .00045 | .0002 | 7.5 | do. | 28 | |
| 6 | .0004 | .0005 | .0003 | 7.5 | do. | 34 | |
| 7 | .0004 | .0006 | .0002 | 7.5 | do. | 40 | |
| 8 | Trace | Trace | Trace | - | None | 10 | |
| 9 | Trace | Trace | Trace | - | do. | 15 | |
| 10 | .0003 | .0003 | Trace | 8.2 | do. | 20 | |
| 11 | .0003 | .00035 | Trace | 8.0 | do. | 25 | |
| 12 | .0003 | .0004 | .0004 | 7.7 | do. | 30 | |
| 13 | .0004 | .0006 | .00045 | 8.2 | do. | 40 | |
| 14 | .0003 | .0007 | .0001 | 7.5 | 1 1/8" | 10 | |
| 15 | .00055 | .00115 | .0002 | 7.5 | do. | 16 | |
| 16 | .0005 | .0008 | .0002 | 7.5 | do. | 22 | |
| 17 | .0005 | .00075 | .0003 | 7.5 | do. | 28 | |
| 18 | .0007 | .00115 | .0004 | 7.5 | do. | 34 | |
| 19 | .00055 | .0012 | .0003 | 8.3 | do. | 40 | |
| 20 | .0004 | .0007 | Trace | 7.5 | 1 1/8" | 10 | |
| 21 | .00045 | .00095 | Trace | 7.5 | do. | 15 | |
| 22 | .00045 | .00085 | .0003 | 7.5 | do. | 20 | |
| 23 | .0005 | .0008 | .0003 | 8.0 | do. | 25 | |
| 24 | .00055 | .00085 | .0003 | 7.7 | do. | 30 | |
| 25 | .00055 | .00105 | .0004 | 7.6 | do. | 40 | |

Vehicle: Brill Trolley Bus No. 1682

Observation Point Downstairs in Dr. Beattie's House
Vehicle Running Track Outer Strip Near Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. Vert. Comp. c.p.s. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 26 | .0006 | .00125 | .0003 | 7.5 | 2 1/16" | 22 | |
| 27 | .0006 | .0011 | .0002 | 7.5 | do. | 10 | |
| 28 | .00065 | .00135 | .0002 | 7.4 | do. | 16 | |
| 29 | .0005 | .00115 | .0003 | 7.5 | do. | 22 | |
| 30 | .0006 | .0011 | .0003 | 7.6 | do. | 28 | |
| 31 | .00075 | .0014 | .0003 | 7.7 | do. | 34 | |
| 32 | .0006 | .00125 | .0003 | 7.6 | do. | 38 | |
| 33 | .00065 | .0013 | .0003 | 7.6 | do. | 16 | |
| 34 | .00055 | .0011 | .0003 | 7.8 | do. | 22 | |
| 35 | .0006 | .0011 | .0004 | 7.8 | do. | 28 | |
| 36 | .0007 | .0015 | .0003 | 7.8 | do. | 34 | |
| 37 | .00055 | .0013 | .0003 | 7.8 | do. | 40 | |
| 38 | .00045 | .00105 | Trace | 7.1 | 2 1/16" | 10 | |
| 39 | .0007 | .0013 | Trace | 7.0 | do. | 15 | |
| 40 | .0005 | .00135 | .0002 | 7.3 | do. | 20 | |
| 41 | .0006 | .0013 | .0003 | 7.3 | do. | 25 | |
| 42 | .00065 | .00145 | .0004 | 7.1 | do. | 30 | |
| 43 | .0007 | .00155 | .0004 | 7.7 | do. | 40 | |
| 44 | .00084 | .00155 | .0003 | 7.0 | 3 1/16" | 10 | |
| 45 | .0008 | .0016 | .0003 | 6.8 | do. | 16 | |
| 46 | .0007 | .0015 | .0002 | 7.0 | do. | 22 | |
| 47 | .0008 | .0017 | .0003 | 7.0 | do. | 28 | |
| 48 | .0009 | .0019 | .0003 | 7.0 | do. | 34 | |
| 49 | .00085 | .0020 | .0003 | 7.5 | do. | 40 | |
| 50 | .0007 | .00145 | .0002 | 6.7 | 3 1/16" | 10 | |
| 51 | .00075 | .00155 | .0003 | 6.7 | do. | 15 | |
| 52 | .0008 | .0016 | .0003 | 6.8 | do. | 20 | |
| 53 | .00085 | .0016 | .0003 | 6.7 | do. | 25 | |
| 54 | .0006 | .0017 | .00035 | 6.9 | do. | 30 | |
| 55 | .0009 | .00195 | .00045 | 7.3 | do. | 40 | |

Vehicle: Brill Trolley Bus. No.1682

Observation Point Downstairs in Dr. Beattie's House
Vehicle Running Track Centre Strip Near Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq.Vert. Comp.c.p.s. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 56 | - | .0002 | - | - | None | 10 | |
| 57 | - | .0002 | - | - | do. | 16 | |
| 58 | - | .00025 | - | - | do. | 22 | |
| 59 | - | .0003 | - | - | do. | 28 | |
| 60 | - | .00035 | - | - | do. | 34 | |
| 61 | - | .00035 | - | - | do. | 40 | |
| 62 | Missed | | | | 1 1/8" | 10 | |
| 63 | .0004 | .00085 | Trace | - | do. | 16 | |
| 64 | .0004 | .0008 | .0002 | 7.4 | do. | 22 | |
| 65 | .0004 | .00095 | .0002 | 7.5 | do. | 28 | |
| 66 | .0004 | .0009 | .0003 | 7.8 | do. | 34 | |
| 67 | .00035 | .0007 | .0002 | 7.4 | do. | 40 | |
| 68 | .0004 | .0007 | Trace | 8.2 | 1 1/8" | 10 | |
| 69 | .0004 | .00085 | .0002 | 7.7 | do. | 16 | |
| 70 | .0004 | .0009 | .0003 | 7.8 | do. | 22 | |
| 71 | .0004 | .0009 | .0002 | 7.7 | do. | 28 | |
| 72 | .00035 | .00075 | .0003 | 8.0 | do. | 34 | |
| 73 | .0004 | .0007 | .0004 | 7.9 | do. | 40 | |
| 74 | .0006 | .00115 | - | 8.1 | 2 1/16" | 10 | |
| 75 | .0005 | .0012 | Trace | 7.2 | do. | 16 | |
| 76 | .0006 | .00135 | .0002 | 7.3 | do. | 22 | |
| 77 | .0005 | .0014 | .0003 | 7.6 | do. | 28 | |
| 78 | .0006 | .0012 | .0004 | 7.8 | do. | 34 | |
| 79 | .0004 | .0009 | .0004 | 7.7 | do. | 40 | |

Vehicle: Brill Trolley Bus No. 1682

Observation Point Downstairs in Dr. Beattie's House
Vehicle Running Track Centre Strip Near Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. Vert. Comp. c.p.s. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 80 | .0006 | .00125 | .0001 | 7.7 | 2 1/16" | 10 | |
| 81 | .00055 | .0012 | .0002 | 7.1 | do. | 16 | |
| 82 | .0005 | .0013 | .0003 | 7.1 | do. | 22 | |
| 83 | .0006 | .00125 | .0003 | 7.4 | do. | 28 | |
| 84 | .00055 | .0013 | .0003 | 7.9 | do. | 34 | |
| 85 | .0004 | .00085 | .0004 | 7.9 | do. | 40 | |
| 86 | .0005 | .0008 | .0001 | 7.7 | 3 1/16" | 10 | |
| 87 | .0004 | .00095 | .0002 | 6.8 | do. | 16 | |
| 88 | .0006 | .00125 | .0003 | 6.8 | do. | 22 | |
| 89 | .0006 | .00135 | .0003 | 7.0 | do. | 28 | |
| 90 | .0006 | .00145 | .0002 | 7.1 | do. | 34 | |
| 91 | .0005 | .0012 | .0002 | 7.7 | do. | 40 | |
| 92 | .0005 | .0011 | .0002 | 7.0 | 3 1/16" | 10 | |
| 93 | .0005 | .00115 | .0002 | 6.7 | do. | 16 | |
| 94 | .0006 | .00135 | .0002 | 6.7 | do. | 22 | |
| 95 | .0006 | .00135 | .0002 | 6.8 | do. | 28 | |
| 96 | .0006 | .0015 | .0003 | 7.1 | do. | 34 | |
| 97 | .0005 | .00105 | .0003 | 7.2 | do. | 40 | |
| 98 | .00025 | .00045 | - | 7.1 | 3 1/16" | 10 | Braking Test |
| 99 | .0003 | .0007 | - | 6.6 | do. | 16 | |
| 100 | .0002 | .00065 | - | 7.3 | do. | 22 | |
| 101 | .0005 | .00105 | - | 6.5 | do. | 28 | |
| 102 | .00055 | .00125 | - | 7.5 | do. | 30 | Acceleration Test |

Vehicle: Brill Trolley Bus No. 1682

Observation Point Downstairs in Dr. Beattie's House
Vehicle Running Track Centre Strip ... Far Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. Vert. Comp. c.p.s. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 103 | - | Trace | - | - | None | 10 | |
| 104 | - | .0001 | - | - | do. | 16 | |
| 105 | - | .0002 | - | - | do. | 22 | |
| 106 | - | .0003 | - | - | do. | 28 | |
| 107 | .0003 | .00045 | .0002 | 8.0 | do. | 34 | |
| 108 | .0003 | .00055 | .0002 | 8.3 | do. | 35 | |
| 109 | .0003 | .00045 | .0002 | 8.0 | 1 1/8" | 10 | |
| 110 | .0004 | .00075 | .0002 | 8.1 | do. | 16 | |
| 111 | .0004 | .00075 | .0003 | 7.7 | do. | 22 | |
| 112 | .0005 | .00085 | .0003 | 7.5 | do. | 28 | |
| 113 | .0005 | .0007 | .0003 | 7.5 | do. | 34 | |
| 114 | .0004 | .00065 | .0002 | 7.5 | do. | 40 | |
| 115 | .00055 | .00095 | .00045 | 7.2 | 2 1/16" | 10 | |
| 116 | .0007 | .0012 | .0005 | 7.0 | do. | 16 | |
| 117 | .0006 | .0012 | .0005 | 7.3 | do. | 22 | |
| 118 | .00055 | .0011 | .0003 | 7.3 | do. | 28 | |
| 119 | .00055 | .0010 | .0004 | 7.3 | do. | 34 | |
| 120 | .00055 | .00095 | .0005 | 7.3 | do. | 40 | |
| 121 | .00055 | .00105 | .00055 | 6.5 | 3 1/16" | 10 | |
| 122 | .0006 | .00135 | .0006 | 6.4 | do. | 16 | |
| 123 | .0007 | .00145 | .0006 | 6.5 | do. | 22 | |
| 124 | .0007 | .00155 | .00065 | 6.7 | do. | 28 | |
| 125 | .00075 | .00165 | .0007 | 6.8 | do. | 34 | |
| 126 | .0007 | .0015 | .00055 | 6.8 | do. | 40 | |

Vehicle: Brill Trolley Bus. No. 1682

Observation Point Downstairs in Dr. Beattie's House
Vehicle Running Track Outer Strip Far Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. Vert. Comp. c.p.s. | Ramp. | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 127 | - | - | - | - | None | 10 | |
| 128 | None | .0002 | None | - | do. | 16 | |
| 129 | Trace | .0003 | None | 7.7 | do. | 22 | |
| 130 | .0001 | .0003 | Trace | 8.3 | do. | 28 | |
| 131 | .0002 | .0003 | .0001 | 6.9 | do. | 34 | |
| 132 | .0003 | .0005 | .0002 | 8.1 | do. | 40 | |
| 133 | .0004 | .0005 | Trace | 7.4 | 1 1/8" | 10 | |
| 134 | .0006 | .00075 | Trace | 7.5 | do. | 16 | |
| 135 | .0004 | .0008 | .0001 | 7.3 | do. | 22 | |
| 136 | .0003 | .0007 | .0001 | 7.9 | do. | 28 | |
| 137 | .0003 | .0005 | .0003 | 7.0 | do. | 34 | |
| 138 | .0003 | .0006 | .0001 | 7.3 | do. | 40 | |
| 139 | .0004 | .0007 | Trace | 7.4 | 1 1/8" | 10 | |
| 140 | .0004 | .0008 | .0001 | 7.7 | do. | 16 | |
| 141 | .0004 | .00085 | .0001 | 7.4 | do. | 22 | |
| 142 | .0005 | .0007 | .0001 | 7.7 | do. | 28 | |
| 143 | .0003 | .0005 | .0002 | 6.9 | do. | 34 | |
| 144 | .0005 | .0007 | .0002 | 7.4 | do. | 40 | |
| 145 | .00055 | .0011 | .0001 | 6.9 | 2 1/16" | 10 | |
| 146 | .00055 | .0011 | .0002 | 6.9 | do. | 16 | |
| 147 | .00055 | .0011 | .0002 | 7.5 | do. | 22 | |
| 148 | .0005 | .0011 | .0003 | 7.1 | do. | 28 | |
| 149 | .00045 | .0009 | .0003 | 7.3 | do. | 34 | |
| 150 | .00045 | .0008 | .0002 | 7.0 | do. | 40 | |

Vehicle: Brill Trolley Bus No. 1682

Observation Point Downstairs in Dr. Beattie's House
Vehicle Running Track Outer Strip  Far Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. Vert. Comp. c.p.s. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 151 | .0005 | .00105 | .0003 | 6.4 | 2 1/16" | 10 | |
| 152 | .0005 | .00105 | .0004 | 6.8 | do. | 16 | |
| 153 | .0006 | .00105 | .0003 | 7.1 | do. | 22 | |
| 154 | .0005 | .00095 | .0003 | 7.3 | do. | 28 | |
| 155 | .00045 | .0008 | .0004 | 7.3 | do. | 34 | |
| 156 | .0005 | .00095 | .0003 | 7.2 | do. | 40 | |
| 157 | | .0011 | | 6.3 | 3 1/16" | 10 | |
| 158 | | .00155 | | 6.4 | do. | 16 | |
| 159 | | .00155 | | 6.4 | do. | 22 | |
| 160 | | .00155 | | 6.4 | do. | 28 | |
| 161 | | .0015 | | 7.0 | do. | 34 | |
| 162 | | .00095 | | 6.7 | do. | 40 | |
| 163 | .00065 | .0013 | | 6.3 | 3 1/16" | 10 | |
| 164 | .0008 | .00155 | .00055 | 6.4 | do. | 16 | |
| 165 | .0007 | .00155 | .0005 | 6.4 | do. | 22 | |
| 166 | .00085 | .00155 | .0005 | 6.5 | do. | 28 | |
| 167 | .00085 | .0015 | .0005 | 6.5 | do. | 34 | |
| 168 | .0006 | .0013 | .0005 | 6.8 | do. | 40 | |

Vehicle: Brill Trolley Bus No. 1682

Observation Point ..Upstairs in Dr. Beattie's House
Vehicle Running Track .Outer Strip Near Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. c.p.s. Long. | Vert. | Trans. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 169 | .0019 | .0015 | .0006 | | | | 3 1/16" | 10 | |
| 170 | .0024 | .00205 | .0009 | | | | do. | 16 | |
| 171 | - | - | - | | | | do. | 22 | Paper jammed, rec.spoiled |
| 172 | - | - | - | | | | do. | 28 | do. |
| 173 | - | - | - | | | | do. | 34 | do. |
| 174 | - | - | - | | | | do. | 40 | do. |
| 175 | .0019 | .0015 | .0007 | 7.0 | 6.4 | 6.6 | 3 1/16" | 10 | |
| 176 | .0025 | .0020 | .0008 | 7.0 | 6.7 | 6.3 | do. | 16 | |
| 177 | .0022 | .0017 | .0008 | 7.9 | 7.5 | 6.5 | do. | 22 | |
| 178 | .0026 | .00225 | .0008 | 6.9 | 6.9 | 6.4 | do. | 28 | |
| 179 | .0026 | .00225 | .00095 | 7.5 | 7.5 | 6.6 | do. | 34 | |
| 180 | .003 | .0024 | .001 | 8.2 | 7.7 | 6.7 | do. | 40 | |
| 181 | .0016 | .0085 | .0017 | | 50 | | - | - | These are records of a single jump on floor of Dr. Beattie's house upstairs. Instrument located as for above tests. |
| 182 | .0017 | .0087 | .0015 | | 50 | | - | - | |
| 183 | .0048 | .0121 | .0047 | | 51.3 | | - | - | These are records of a single jump on floor of Dr. Beattie's house downstairs. Instrument located downstairs. |
| 184 | .0040 | .0104 | .004 | | 52.5 | | - | - | |

Vehicle: Gasoline Bus No. 177 wt. 15,200 lbs.

Observation Point Downstairs in Dr. Beattie's House
Vehicle Running Track Outer Strip Near Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. Vert. Comp. c.p.s. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 185 | Trace | Trace | Trace | - | None | 10 | |
| 186 | Trace | .00015 | Trace | 6.9 | do. | 16 | |
| 187 | Trace | .00035 | Trace | 7.5 | do. | 22 | |
| 188 | .0002 | .00045 | Trace | 7.1 | do. | 28 | |
| 189 | .00015 | .0005 | Trace | - | do. | 34 | |
| 190 | .0003 | .00055 | .0004 | - | do. | 40 | |
| 191 | Trace | Trace | Trace | - | None | 10 | |
| 192 | Trace | .0002 | Trace | 8.3 | do. | 16 | |
| 193 | Trace | .00035 | Trace | 7.7 | do. | 22 | |
| 194 | .00025 | .0005 | .00025 | 8.0 | do. | 28 | |
| 195 | .0002 | .0005 | .00035 | 8.4 | do. | 34 | |
| 196 | .00025 | .00045 | .00025 | 6.8 | do. | 40 | |
| 197 | .0003 | .0006 | Trace | 7.3 | 1 1/8" | 10 | |
| 198 | .00035 | .00065 | Trace | 6.8 | do. | 16 | |
| 199 | .0003 | .0007 | .0002 | 6.9 | do. | 22 | |
| 200 | .0003 | .0007 | .00025 | 7.3 | do. | 28 | |
| 201 | .00035 | .0008 | .0003 | 7.6 | do. | 34 | |
| 202 | .00035 | .0008 | .0003 | 7.0 | do. | 40 | |
| 203 | .0002 | .00065 | Trace | 7.1 | 1 1/8" | 10 | |
| 204 | .00035 | .0007 | Trace | 7.1 | do. | 16 | |
| 205 | .0003 | .00065 | Trace | 7.3 | do. | 22 | |
| 206 | .00035 | .00075 | .0002 | 7.1 | do. | 28 | |
| 207 | .00035 | .00075 | .0003 | 7.7 | do. | 34 | |
| 208 | .00035 | .00075 | .0003 | 7.3 | do. | 40 | |

Vehicle: Gasoline Bus No. 177. wt. 15,200 lb.

Observation Point Downstairs, Dr. Beattie's House
Vehicle Running Track Outer Strip - Near Side

| Record No. | Amplitude inches Long. | Vert. | Trans. | Freq. Vert. Comp. c.p.s. | Ramp | Speed m.p.h. | Remarks |
|---|---|---|---|---|---|---|---|
| 209 | .00025 | .0007 | Trace | 7.1 | 2 1/16" | 10 | |
| 210 | .0003 | .0008 | .0002 | 7.9 | do. | 16 | |
| 211 | .0003 | .00075 | .0002 | 7.8 | do. | 22 | |
| 212 | .0004 | .0008 | .00025 | 7.5 | do. | 28 | |
| 213 | .00035 | .0007 | .00035 | 7.1 | do. | 34 | |
| 214 | .00045 | .0011 | .0004 | 6.8 | do. | 40 | |
| 215 | .0003 | .0007 | Trace | 6.9 | 2 1/16" | 10 | |
| 216 | .0003 | .00075 | .0002 | 7.4 | do. | 16 | |
| 217 | .0004 | .00075 | .00025 | 7.5 | do. | 22 | |
| 218 | .0004 | .00075 | .0002 | 7.7 | do. | 28 | |
| 219 | .00025 | .00065 | .0003 | 7.4 | do. | 34 | |
| 220 | .0004 | .0010 | .0003 | 7.0 | do. | 40 | |
| 221 | .00035 | .0009 | Trace | 7.3 | 3 1/16" | 10 | |
| 222 | .0003 | .00075 | .0002 | 7.3 | do. | 16 | |
| 223 | .0004 | .00075 | .0002 | 8.0 | do. | 22 | |
| 224 | .0004 | .0007 | .0003 | 8.3 | do. | 28 | |
| 225 | .0004 | .00075 | .0003 | 7.5 | do. | 34 | |
| 226 | .0005 | .0009 | .00035 | 6.7 | do. | 40 | |
| 227 | .0004 | .0010 | Trace | 7.1 | 3 1/16" | 10 | |
| 228 | .00045 | .0008 | Trace | 7.1 | do. | 16 | |
| 229 | .0004 | .0007 | Trace | 7.4 | do. | 22 | |
| 230 | .0004 | .0009 | .0003 | 8.3 | do. | 28 | |
| 231 | .00035 | .00085 | .0004 | 7.3 | do. | 34 | |
| 232 | .0005 | .00085 | .0004 | 6.6 | do. | 40 | |

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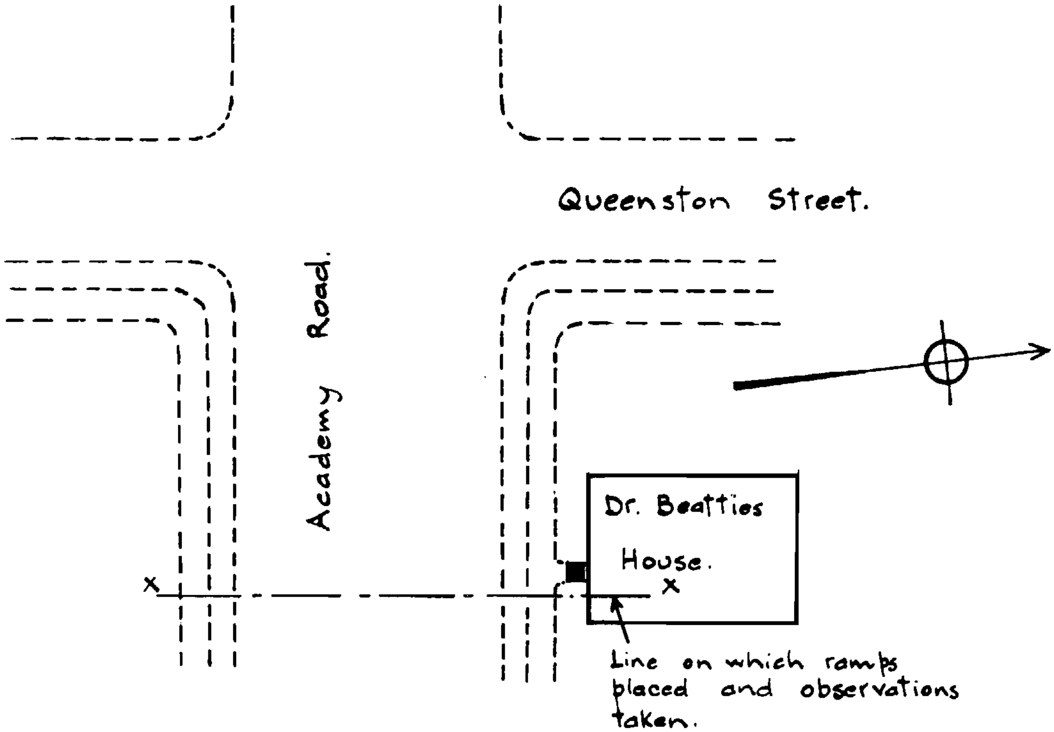



FIG. 1. scale: 1" = 30'

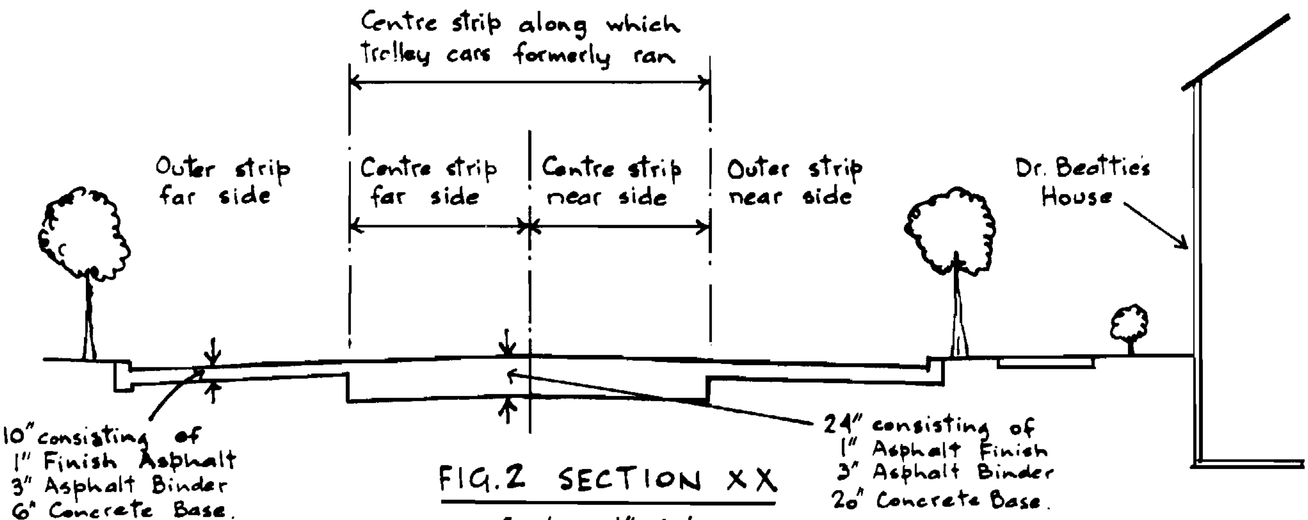
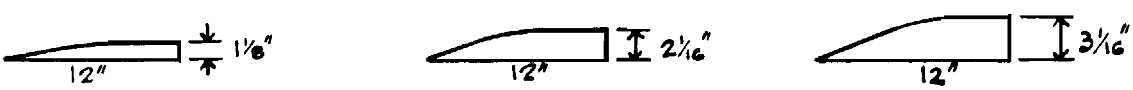



FIG. 2 SECTION XX

Scale: 1" = 10'

FIG. 3 RAMPS OVER WHICH VEHICLES RAN.




| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT: INVESTIGATION OF VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG | SHEET No: 1 |
| CHECKED BY H.B.S. | | DATE: 18-8-1949. |

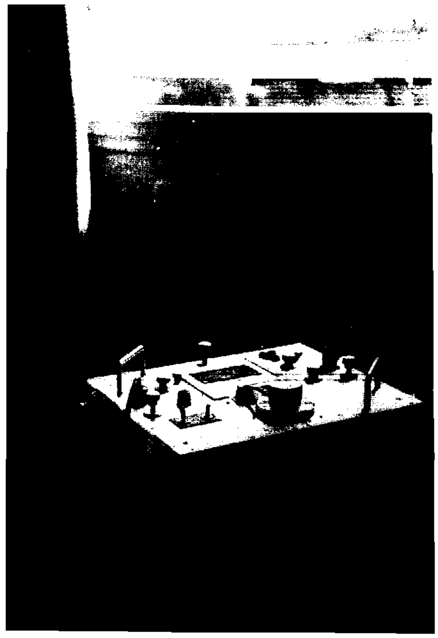


FIG. 4 LEET SEISMOGRAPH LOCATED DOWNSTAIRS IN DR. BEATTIE'S.

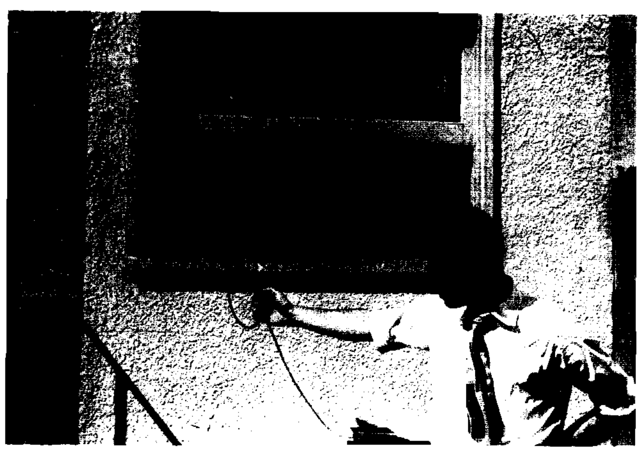


FIG. 5 OPERATION of LEET SEISMOGRAPH BY REMOTE CONTROL SWITCH.

| | | |
|---|---|---|
| DRAWN BY: T.N.B. | PROJECT: INVESTIGATION of VIBRATIONS | SHEET Nº 2 |
| CHECKED BY: T.N.B. | FROM HEAVY VEHICLES IN WINNIPEG. | DATE: 19·8·1949 |

UPSTAIRS OBSERVATION POINT

DOWNSTAIRS OBSERVATION POINT

FIG. 6 DR. BEATTIE'S HOUSE SHOWING UPSTAIRS AND DOWNSTAIRS OBSERVATION POINTS.

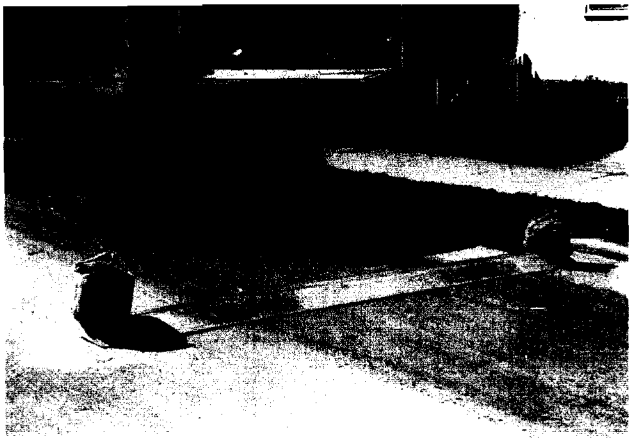
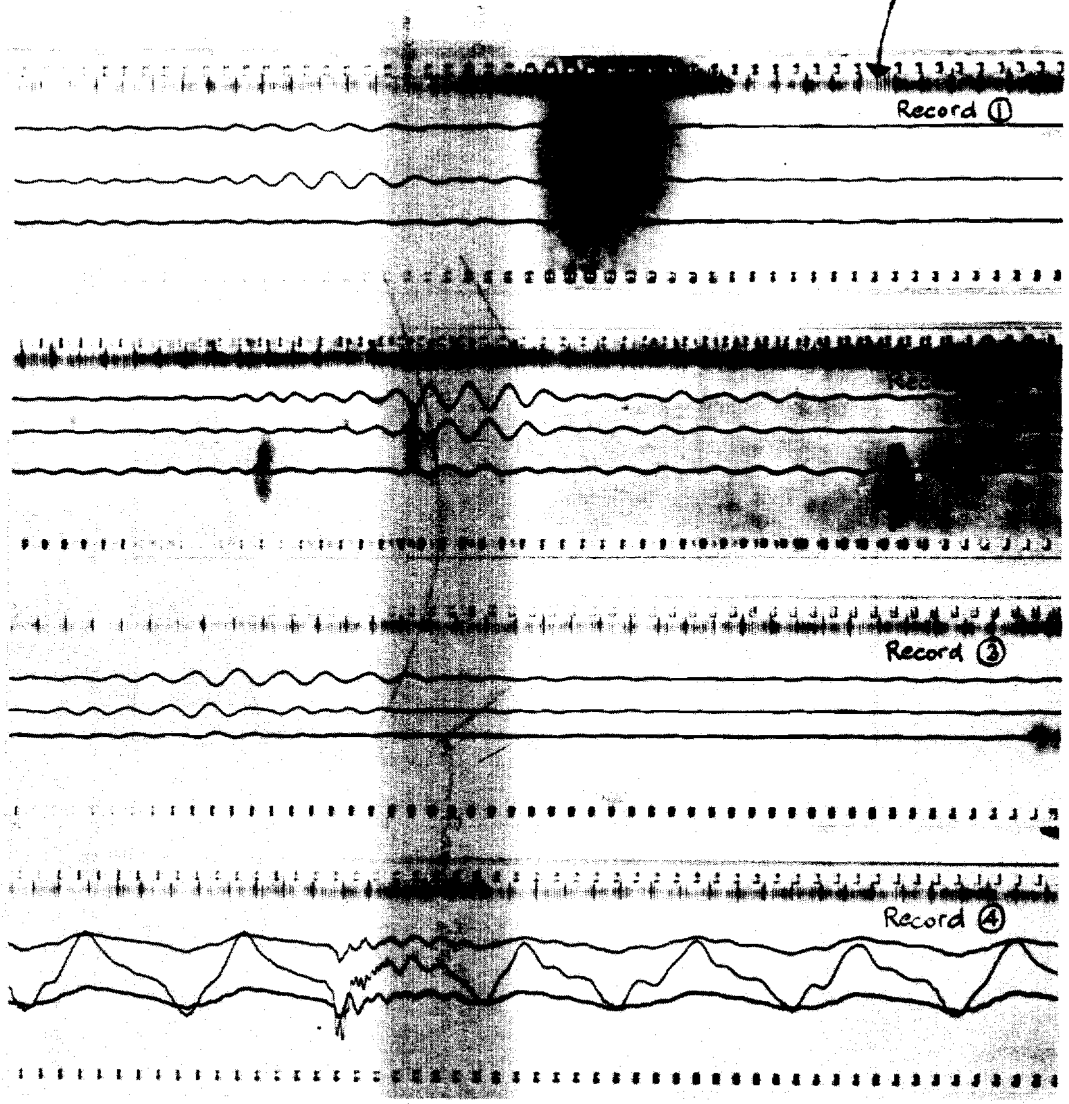


FIG. 7 3 1/16" RAMP IN POSITION IN OUTER STRIP, NEAR SIDE, PRIOR TO TEST.

FIG. 8 BRILL TROLLEY BUS 1682 PASSING OVER 3 1/16" RAMP IN CENTRE STRIP, NEAR SIDE.

SCALE of REPRODUCTIONS : 1/2 FULL SIZE
ACTUAL MAGNIFICATION FACTOR of RECORDS 50:1

TIMING LINES 1/100 SEC. INTERVALS




| VIBRATION COMPONENT | AMPL. IN. | FREQ. C.P.S. | REMARKS. |
|---|---|---|---|
| LONGITUDINAL | ·00085 | - | RECORD of BRILL TROLLEY BUS 1682 TRAVELLING AT 40 M.P.H. OVER 3 1/16" RAMP. RECORD TAKEN DOWNSTAIRS IN DR. BEATTIE'S. |
| VERTICAL | ·002 | 7·5 | |
| TRANSVERSE | ·0003 | | |
| LONGITUDINAL | ·003 | 8·2 | RECORD of BRILL TROLLEY BUS 1682 TRAVELLING AT 40 M.P.H. OVER A 3 1/16" RAMP. RECORD TAKEN UPSTAIRS IN DR. BEATTIE'S |
| VERTICAL | ·0024 | 7·7 | |
| TRANSVERSE | ·001 | 6·7 | |
| LONGITUDINAL | ·002 | 6·8 | RECORD TAKEN UPSTAIRS IN A HOUSE. RECORD IS of BRILL TROLLEY BUS 1682 TRAVELLING AT 40 M.P.H. OVER A 3 1/16" RAMP. |
| VERTICAL | ·0017 | 7·4 | |
| TRANSVERSE | ·0006 | 8·0 | |
| LONGITUDINAL | | 61 | RECORD TAKEN WITH INSTRUMENT IN SAME LOCATION AS Nº 3 ABOVE VIBRATIONS ARE DUE TO A MAN JUMPING ON THE FLOOR. |
| VERTICAL | 5 | 52 | |
| TRANSVERSE | | 50 | |

DRAWN BY: H.B.S. & T.N.B.
CHECKED:

PROJECT: INVESTIGATION of VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG

SHEET Nº 5
DATE: 19·8·1949

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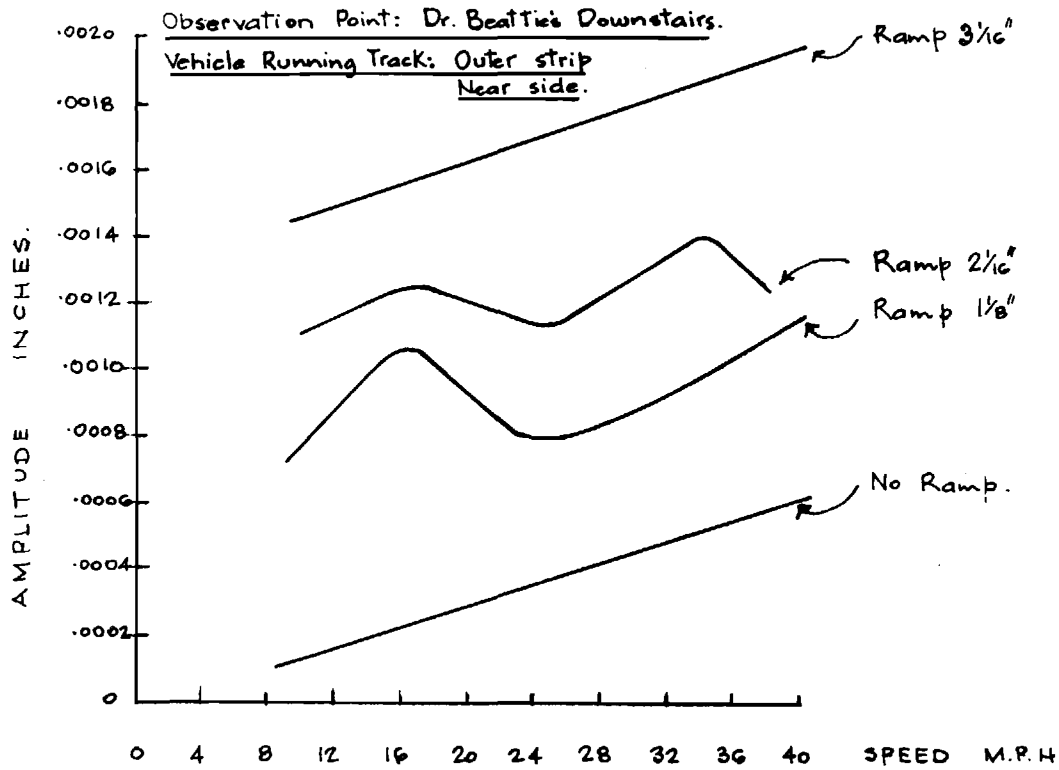


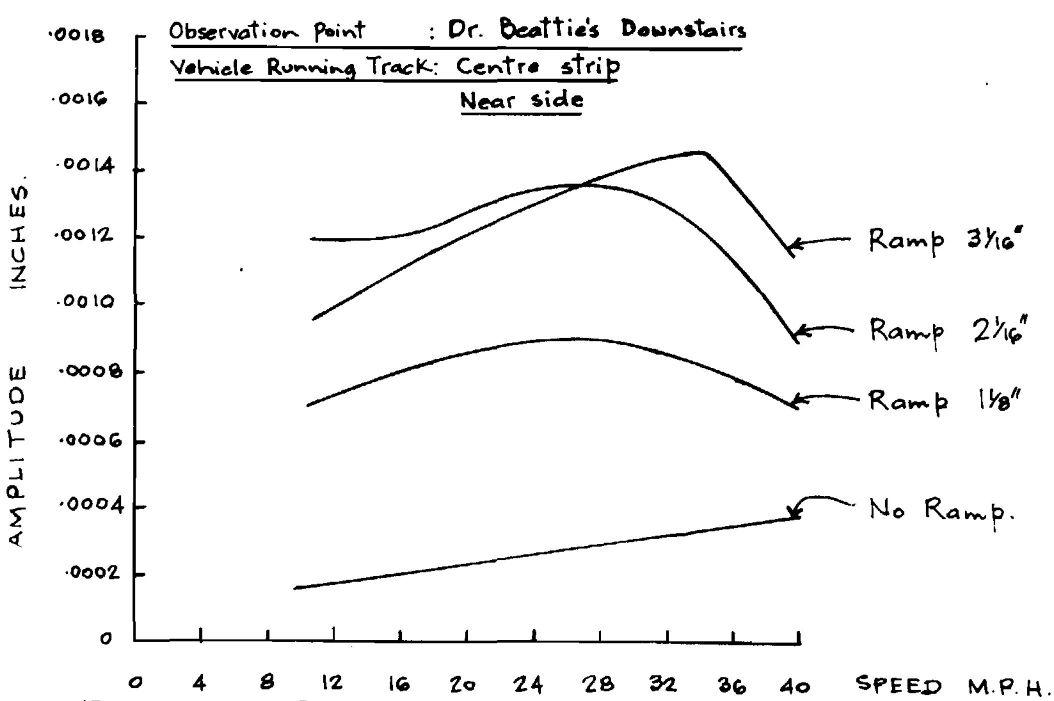


VERTICAL COMPONENTS OF VIBRATIONS FROM DIFFERENT RAMPS.

VEHICLE : BRILL TROLLEY BUS 1682

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT : INVESTIGATION OF VIBRATIONS | SHEET No. 6 |
| CHECKED BY H.B.S. | FROM HEAVY VEHICLES IN WINNIPEG | DATE: 18-8-1949. |

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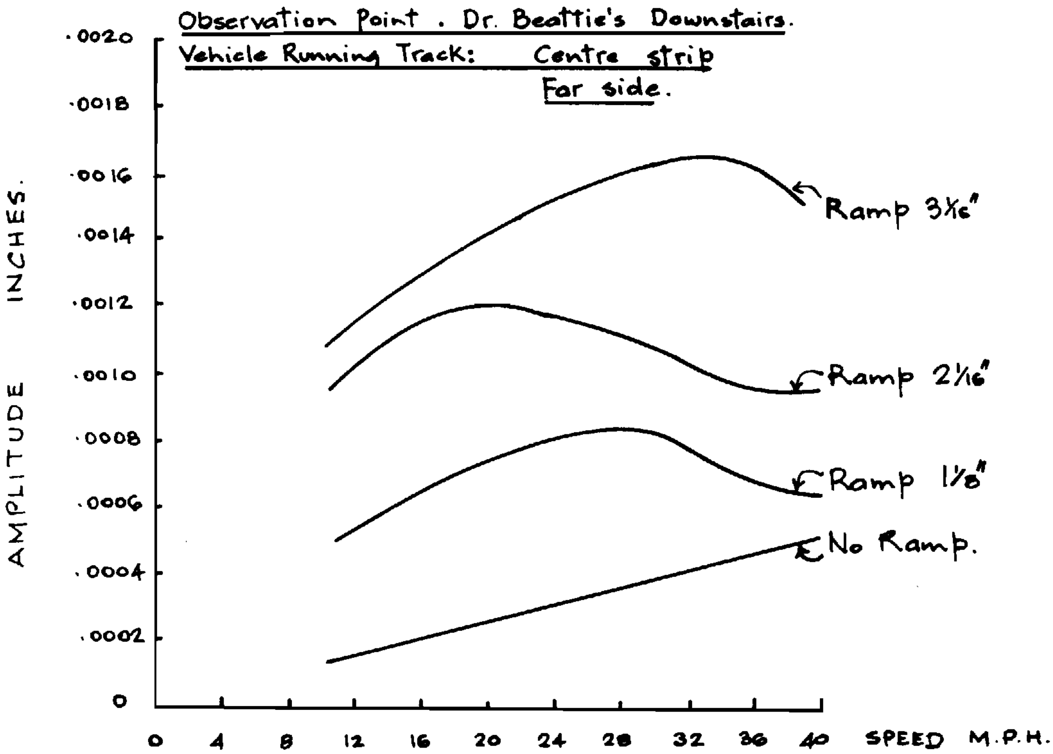


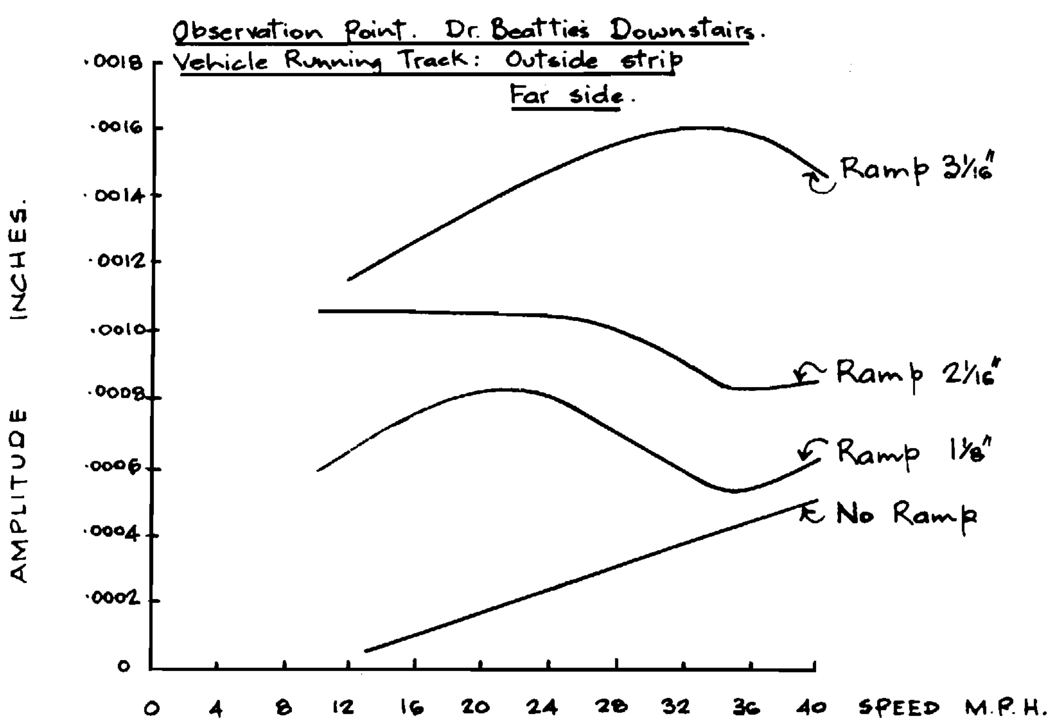


VERTICAL COMPONENTS OF VIBRATIONS FROM DIFFERENT RAMPS.
VEHICLE: BRILL TROLLEY BUS. 1682

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT: INVESTIGATION OF VIBRATIONS | SHEET No 7 |
| CHECKED BY H.B.S. | FROM HEAVY VEHICLES IN WINNIPEG | DATE: 18-8-1949. |

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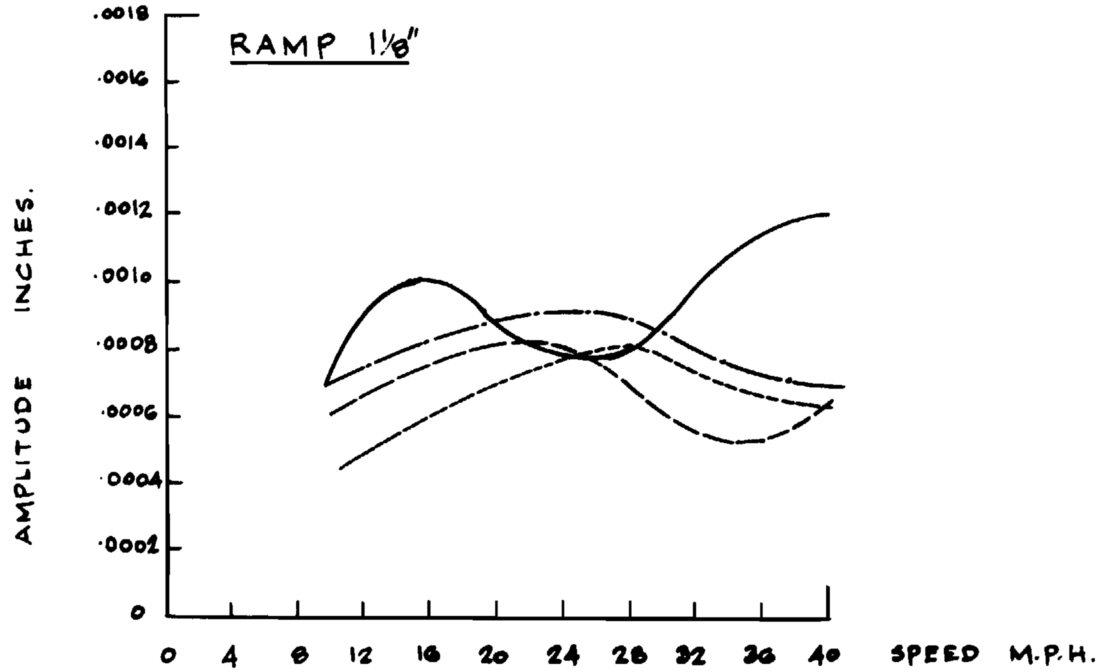
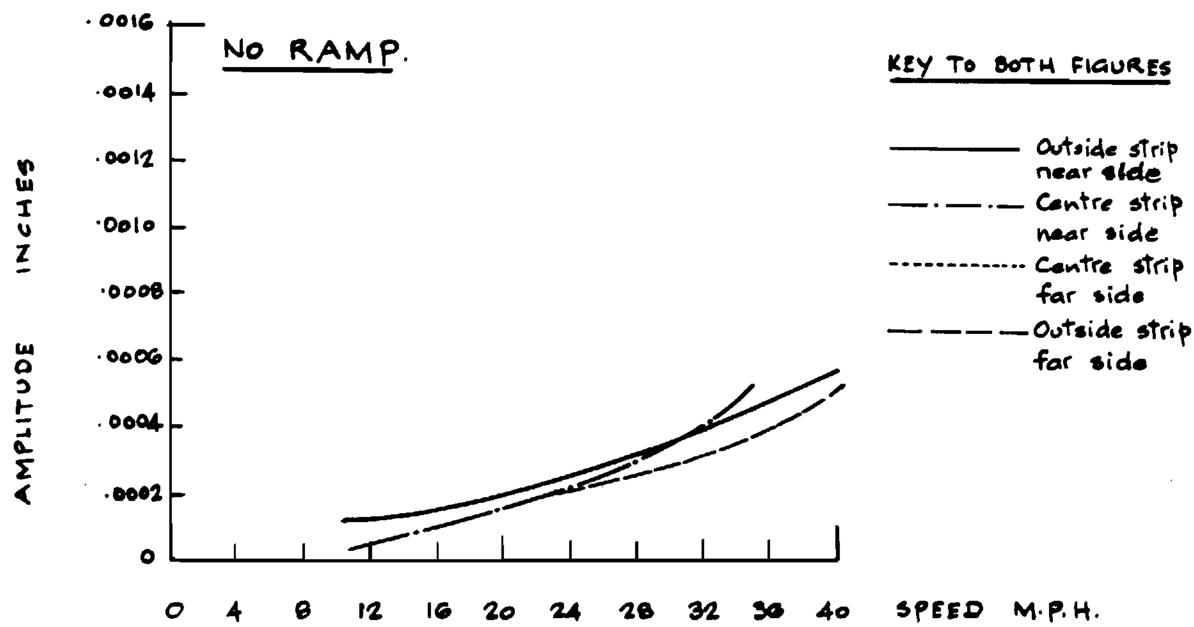
Observation Point : Dr. Beattie's Downstairs.




COMPARISONS OF VERTICAL COMPONENTS OF VIBRATIONS RESULTING FROM THE VARIOUS RUNNING TRACKS

VEHICLE: BRILL TROLLEY BUS 1682

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT : INVESTIGATION OF VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG | SHEET No. 8 |
| CHECKED BY H.B.S. | | DATE : 18-8-1949 |

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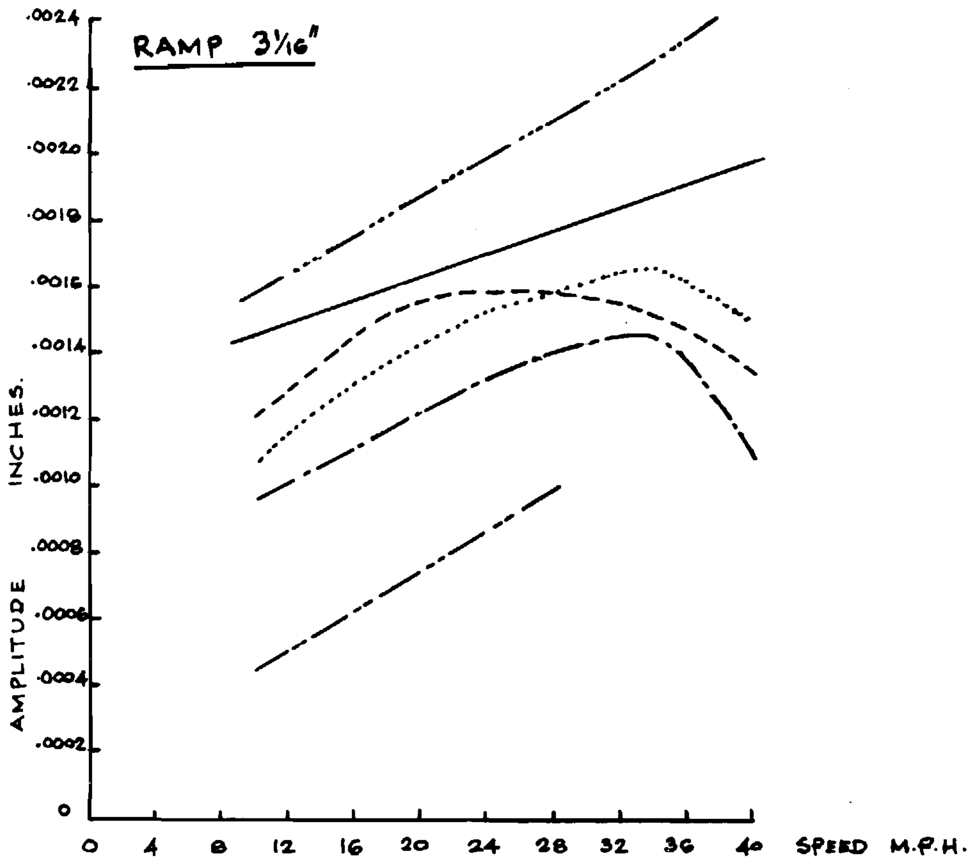
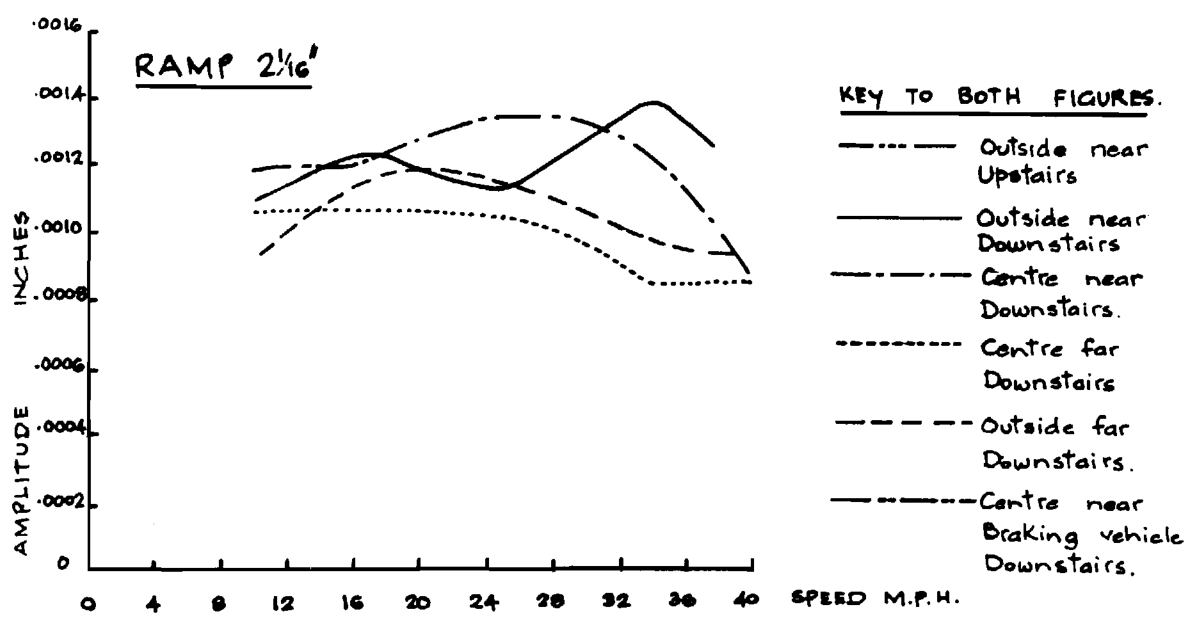


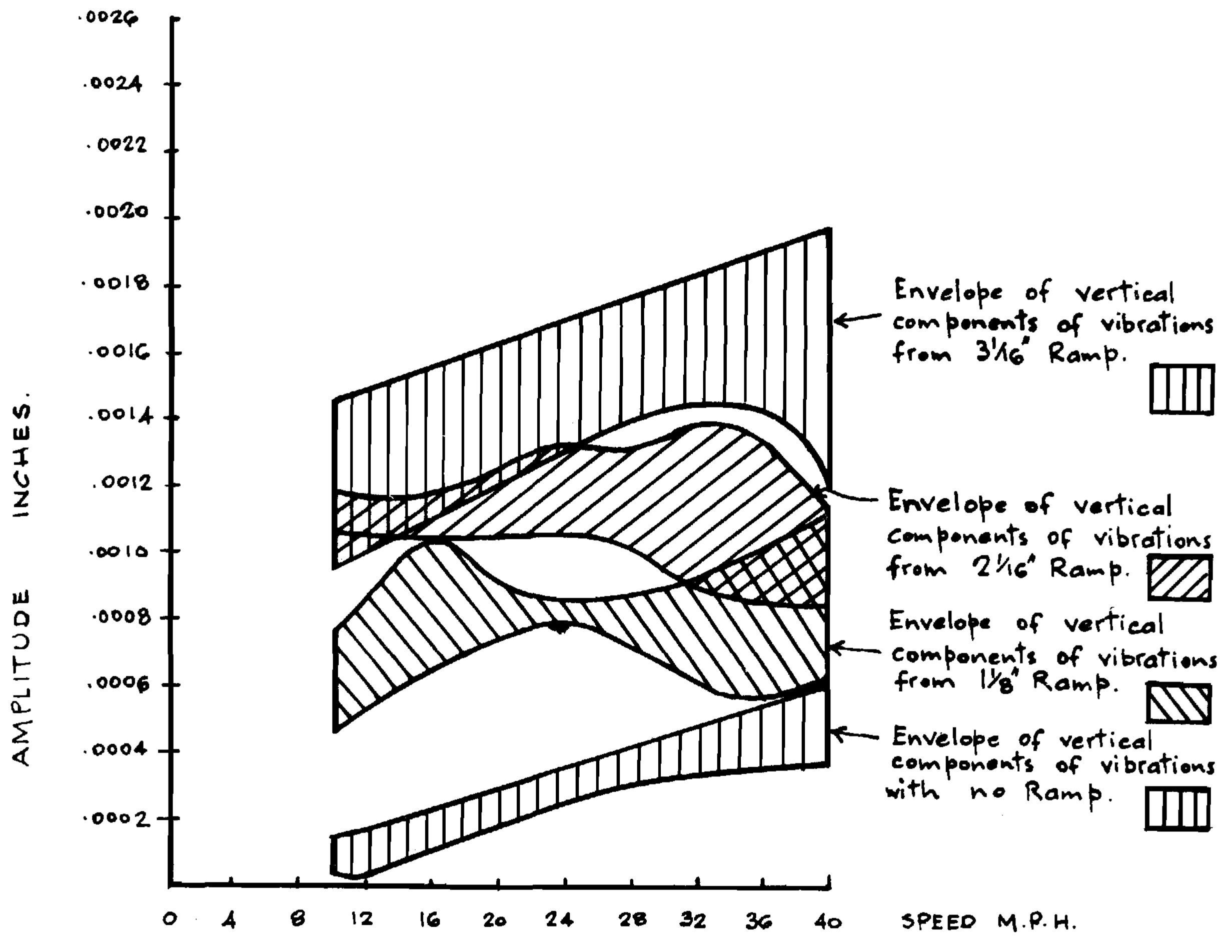

COMPARISONS OF VERTICAL COMPONENTS OF VIBRATIONS RESULTING FROM THE VARIOUS RUNNING TRACKS.

VEHICLE: BRILL TROLLEY BUS 1682

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT: INVESTIGATION OF VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG | SHEET No. 9 |
| CHECKED BY H.B.S. | | DATE: 18-8-1949 |

# GRAPH OF THE ENVELOPES OF INFLUENCE OF THE VARIOUS RAMPS.

Observation Point : Dr. Beattie's Downstairs.




Each envelope encloses, for any one ramp, the complete range of vertical components of vibrations due to different speeds, different running tracks, and different thicknesses of roadway.

VEHICLE: BRILL TROLLEY BUS 1682.

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT: INVESTIGATION OF VIBRATIONS | SHEET NO. 10 |
| CHECKED BY H.B.S. | FROM HEAVY VEHICLES IN WINNIPEG | DATE: 18-8-1949 |

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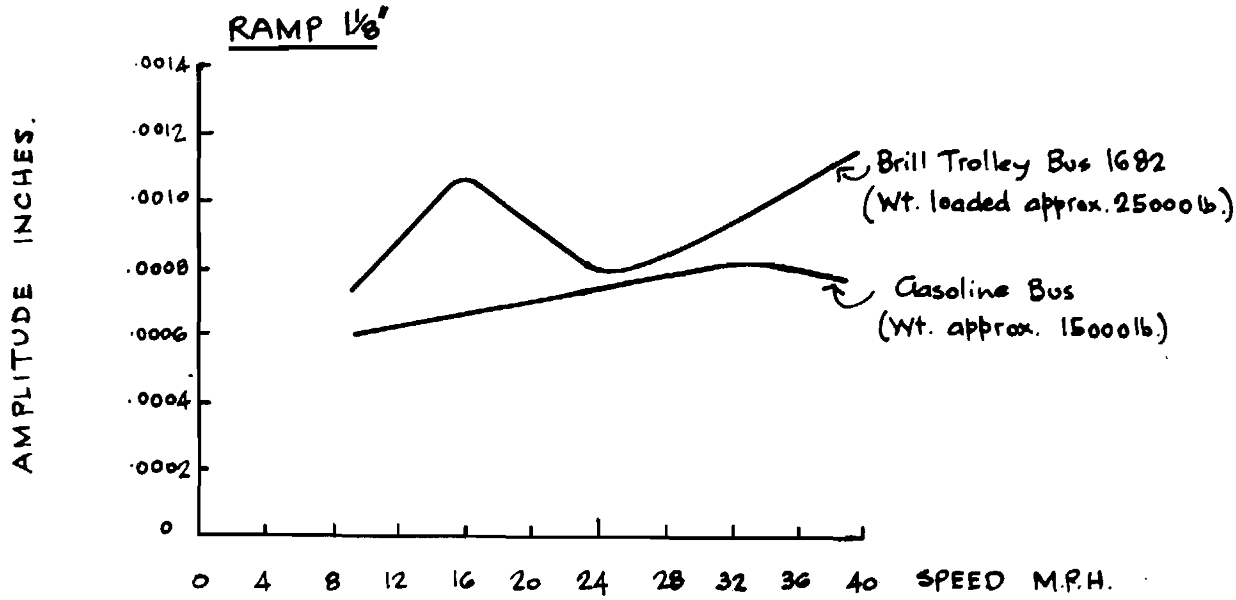
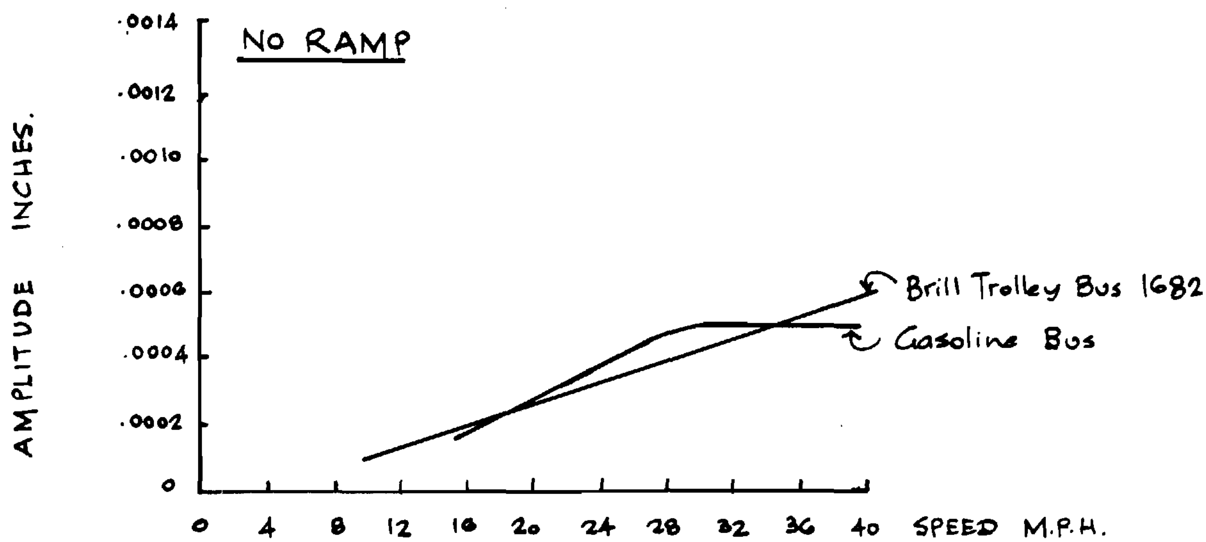
Observation Point: Dr. Beattie's Downstairs.




COMPARISON OF VERTICAL COMPONENTS OF VIBRATIONS FROM A BRILL TROLLEY BUS 1682 AND A GASOLINE BUS.

OUTER STRIP NEAR SIDE

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT: INVESTIGATION OF VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG. | SHEET No. 11 |
| CHECKED BY H.B.S. | | DATE: 19.8.1949 |

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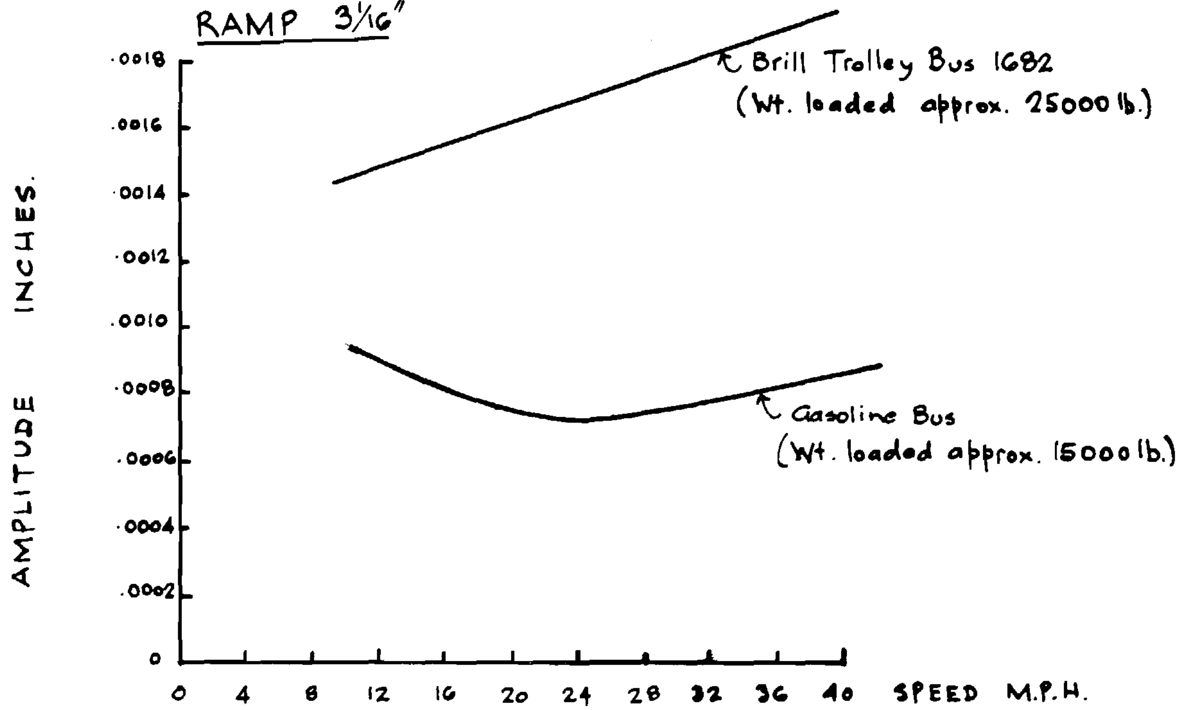
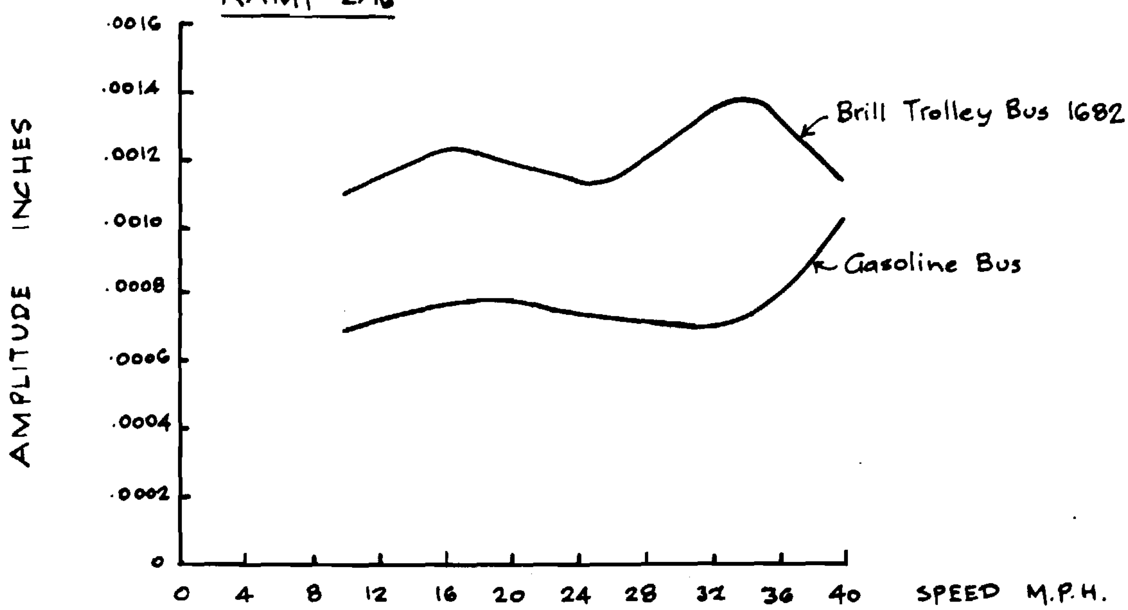
Observation Point: Dr. Beattie's Downstairs.

RAMP 3/16"




RAMP 2 1/16"




COMPARISON OF VERTICAL COMPONENTS OF VIBRATIONS FROM A BRILL TROLLEY BUS 1682 AND A GASOLINE BUS.

OUTER STRIP: NEAR SIDE

| DRAWN BY H.B.S. | PROJECT: INVESTIGATION OF VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG | SHEET No. 12 |
|---|---|---|
| CHECKED BY H.B.S. | | DATE: 19.8.1949 |

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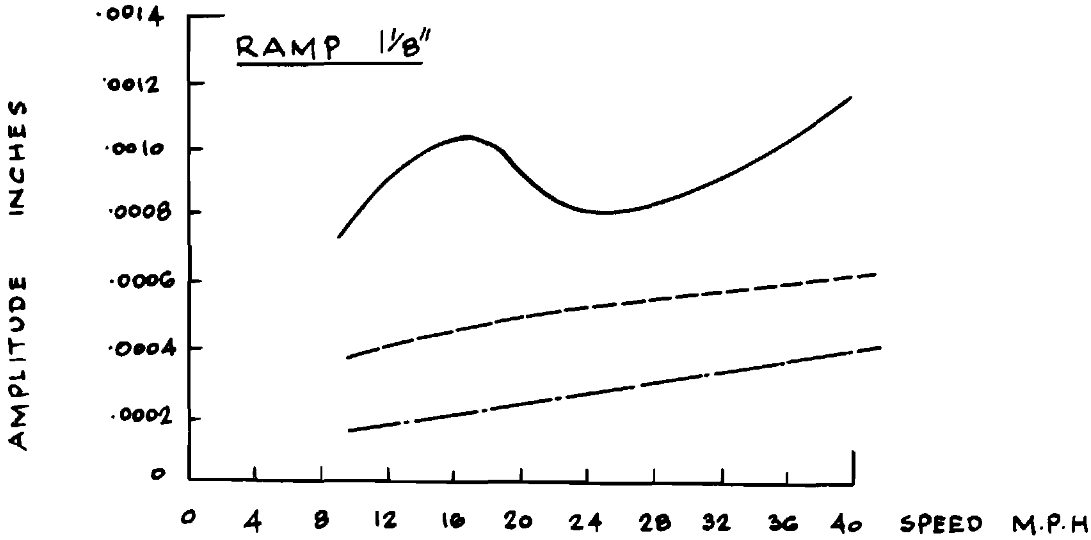
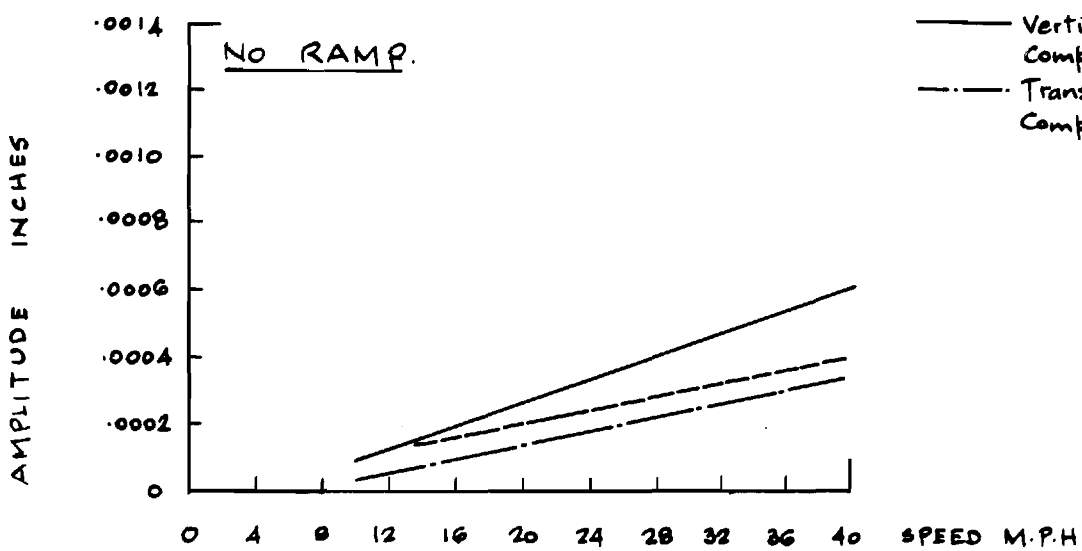
Observation Point : Dr. Beattie's Downstairs.




KEY TO BOTH FIGURES.

- – – – Longitudinal Component
- ——— Vertical Component
- —·— Transverse Component.




COMPARISON OF COMPONENTS OF VIBRATIONS

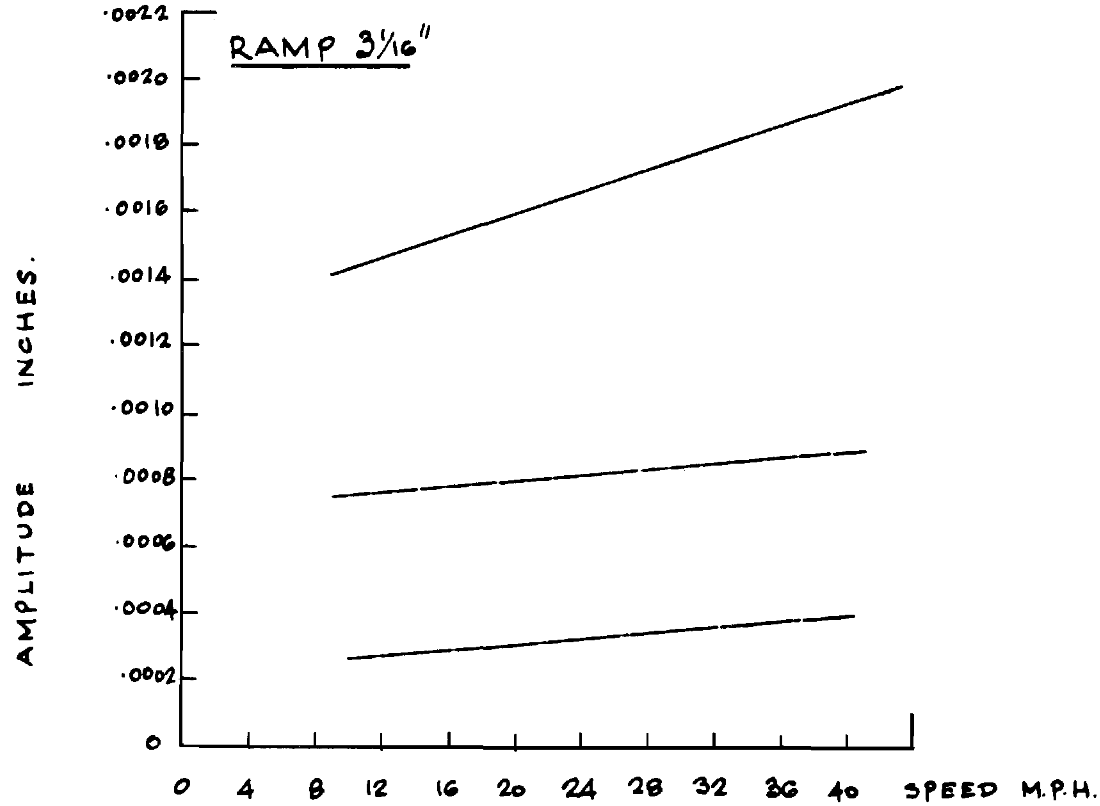
OUTER STRIP NEAR SIDE

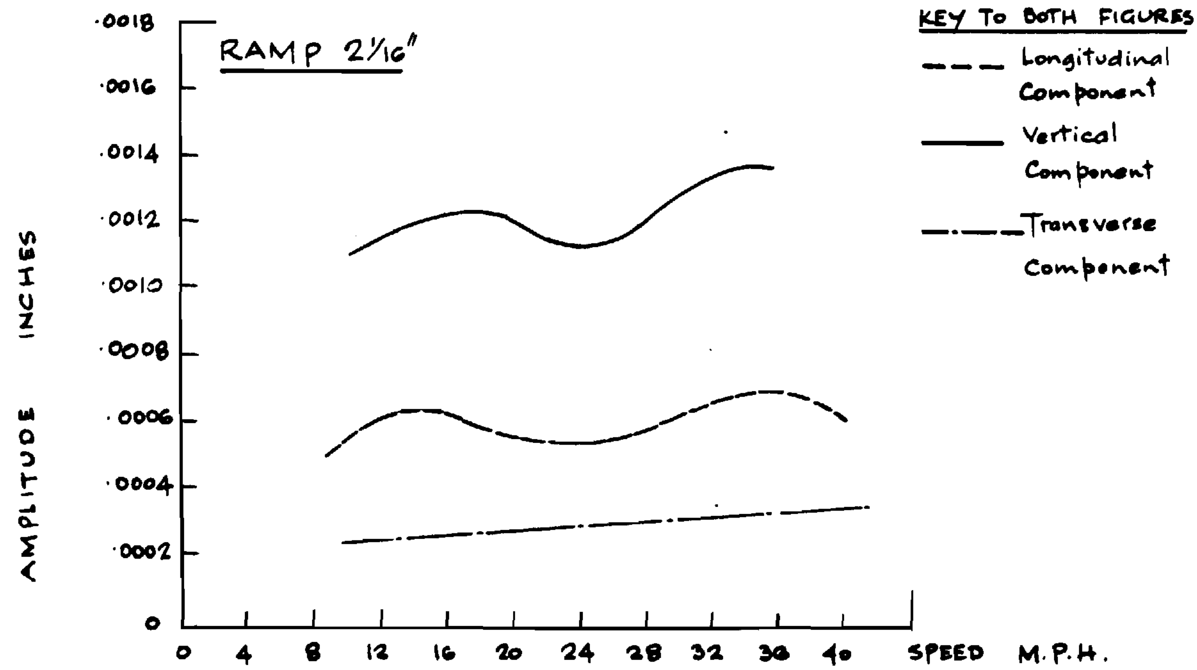
VEHICLE: BRILL TROLLEY BUS 1682

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT: INVESTIGATION OF VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG. | SHEET No. 13 |
| CHECKED BY H.B.S. | | DATE 18-8-1949 |

DIVISION OF BUILDING RESEARCH ○ NATIONAL RESEARCH COUNCIL

Observation Point: Dr. Beattie's Downstairs




COMPARISON OF COMPONENTS OF VIBRATIONS
OUTER STRIP NEAR SIDE
VEHICLE: BRILL TROLLEY BUS 1682.

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT. INVESTIGATION OF VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG. | SHEET NO. 14 |
| CHECKED BY H.B.S. | | DATE: 18-8-1949 |

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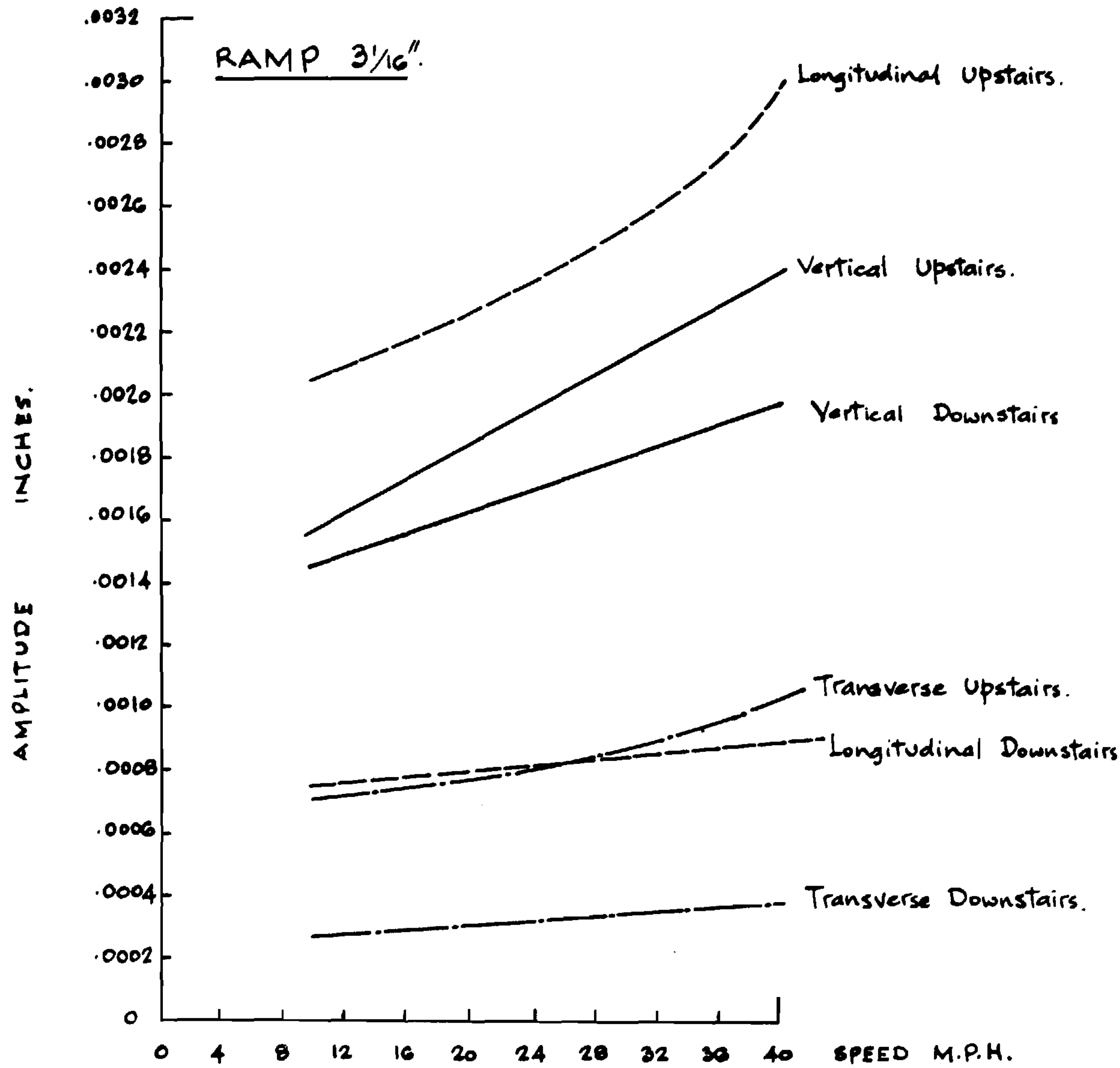
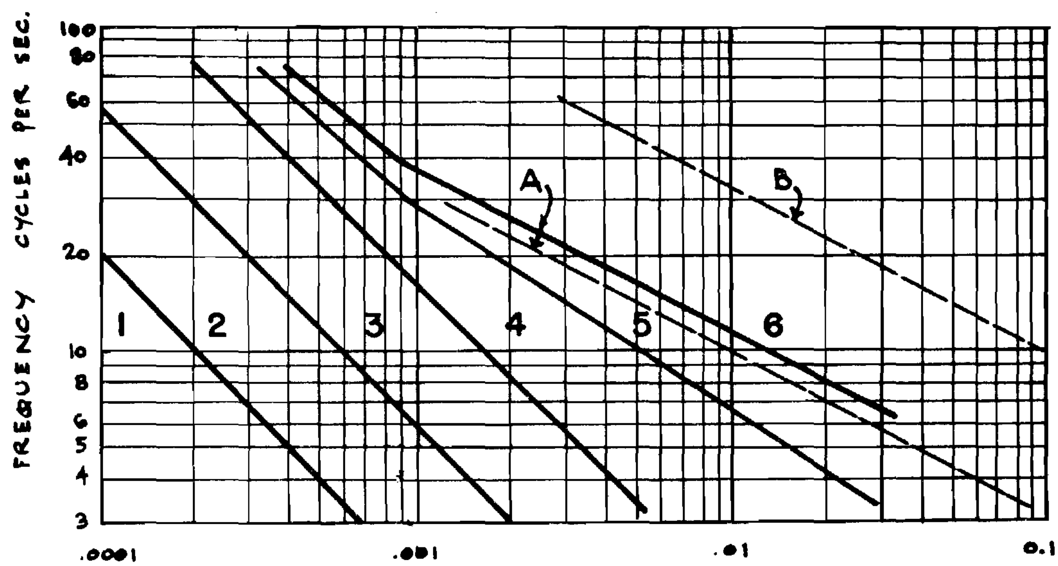



COMPARISON OF VIBRATIONS PRODUCED UPSTAIRS AND DOWNSTAIRS IN DR. BEATTIE'S HOUSE

OUTER STRIP NEAR SIDE

VEHICLE: BRILL TROLLEY BUS 1682

| | | |
|---|---|---|
| DRAWN BY H.B.S. | PROJECT: INVESTIGATION OF VIBRATIONS FROM HEAVY VEHICLES IN WINNIPEG | SHEET No. 15 |
| CHECKED BY H.B.S. | | DATE. 18-8-1949. |




ZONES OF RESPONSE OF HUMANS STANDING TO DIFFERENT INTENSITIES OF THE VERTICAL COMPONENTS OF VIBRATIONS.

| ZONE | RESPONSE |
|---|---|
| 1. | NOT PERCEPTIBLE |
| 2. | SLIGHTLY PERCEPTIBLE |
| 3. | DISTINCTLY PERCEPTIBLE |
| 4. | STRONGLY PERCEPTIBLE |
| 5. | DISTURBING. MAY HAVE DETRIMENTAL EFFECTS, SUCH AS SEVERE HEADACHES, IF OF LONG DURATION. |
| 6. | VERY DISTURBING. MAY HAVE DETRIMENTAL EFFECTS IF OF SHORT DURATION. |

The above diagram is enlarged and reproduced in part from
※ "Die Empfindlichkeit des Menschen gegen Erschütterungen" by H. Reiher and F.J. Meister. Forsch. Gebiete Ingenieurw. 2(11) : 381-386 (1931)
※ "Human Sensitivity to Vibrations."

| | | |
|---|---|---|
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| CHECKED BY H.B.S. | | DATE: 19.8.1949 |