Correspondence.

Mr. H. P. Boulnois agreed with Mr. Wood that the foundation of the carriageway was of primary importance, and many failures had occurred through improper foundations. Sub-drainage was also imperative where water was encountered; it was well known that water was even more destructive to a road than traffic. The Telford foundation of hand-pitched large stones was scientifically correct, as it drained the water from the surface construction of the road, whereas an impervious foundation could not do this. The tests carried out by Mr. Wood to show the movements of a vehicle when passing over obstructions or depressions on the surface of a road were interesting, as they showed that an absolutely smooth surface was most desirable if it could be constructed and maintained in such perfection, and was quite ideal for self-propelled traffic, though possibly slippery for horse traffic. Mr. Wood gave some useful data with regard to the construction of artificial asphalt surfaces, but in practice it was questionable whether such accuracy of grading and percentages could be maintained. It would appear from these experiments that the nearer the composition of some of the best natural rock asphalts could be approached the better. He was of opinion that for some unexplainable cause these rocks did not appear to make such good road surfaces as formerly. He had some considerable experience about 47 years ago with compressed asphalt roads abroad, and they made excellent and durable surfaces, and in this country it was the same; but he had observed for the last few years that this class of road-work appeared to have deteriorated; the asphalt seems to disintegrate and give way under the traffic more quickly than formerly. This could not be due to the change in the traffic, which should be in its favour. Whether the character of the rocks now employed had changed or whether alterations had been made in the methods of "cooking" he did not know, but the results did not seem to be so satisfactory as formerly. Mr. Boulnois.

With reference to Mr. Leeming's Paper, the question of road-corrugation, or the formation of waves on the surface, had been a matter of investigation and contention for some time past, and no very satisfactory conclusions had been arrived at, though the consensus of opinion appeared to be that waves were started by the process of rolling and continued and increased by the traffic, and

Mr. Boulnois. that if the surface of a road could be "punned" or beaten into place, this deformation would not occur to such an extent as it did at present. This contention was confirmed to some extent by the fact that in compressed asphalt and other road formations where rollers were not used there was very little sign of any such deformation. It seemed impossible, however, to prevent the formation of waves where unstable, and resilient, materials were used in the construction of roads, and unless some more rigid construction was employed waves would sooner or later appear. Under these circumstances a more rigid construction seemed to be desirable, and consequently a properly-constructed concrete road-surface would not move and no waves would appear, though possibly slight corrugation might occur in process of time, as it did even on the surface of steel rails. Unfortunately very few trials of un-surfaced concrete roads had been made in this country so that this contention could not be proved, although in the United States of America, many million square yards of such roads had been laid without the appearance of any waves in their surface.

Mr. Bower's Paper dealt with ordinary waterbound macadam roads which had served their purpose in the past, and probably in some localities would have to be constructed in the future, but with tar-treated surfaces. The Author's experiences of road repairs appeared to have been rather unusual as he mentioned holes, in a road of greater depth than 18 inches, and even 4 feet to 8 feet in depth! Such holes could only have been caused by bombs or shells so that one must assume that the Author had been repairing roads at the front. This might also be the reason why he gave a description of the method he adopted for supporting the haunches of a road with timber, a practice that did not recommend itself where permanent work was required, although he was quite right in drawing attention to the necessity for strengthening the haunches of all roads.

Mr. Boulnois was of opinion that the best road construction could not be settled "on paper"; every case should be carefully investigated: climate, gradients, surroundings, class of traffic, necessity for drainage, local materials, and many more conditions affected the question. It was evident, however, that the road of the future would be built on much more scientific lines than had prevailed in the past, and that many roads would have to be designed to carry traffic vastly increased in quantity, weight, and speed.

Dr. Brightmore. Dr. A. W. BRIGHTMORE considered that one of the chief causes of the cross corrugation of road surfaces subjected to fast heavy motor traffic was the fact that the rigidity of the frames of heavy motors ordinarily prevented more than three wheels of the vehicle from being

Dr. Brightmore.

in effective contact with the road at a time. The springs did not act quickly enough to ensure all the four wheels being always in contact with an uneven road, and even if they were in contact, there would often be little load on the fourth wheel. If one of the driving-wheels were free, that wheel would tend to be driven at a greater rate, and when it again came in contact with the road, damage was done to both wheel and road. Longitudinal corrugations appeared to be produced largely owing to the fact that rear-axle driving tended to move the vehicle parallel to its frame, so that the front wheels, when twisted for steering, exerted a force on the road at right angles to the direction of motion of the vehicle.

It was theoretically possible, by means of suitable articulation, to design a motor road-vehicle so that all four wheels would always be in effective contact with the road and take their due proportion of the load, however uneven the road might be; also so that both axles would always be driven in the direction of motion at the instant. The scheme by which this could be effected, was to have a motor on the forecarriage, to articulate the forecarriage to the body by a ball-and-socket or equivalent joint over the front axle, the back of the forecarriage being connected to a slider by a pin radiating (in the central position of the forecarriage) from the centre of the ball to the point on the road midway between the back wheels. The slider would work on a circular segment fixed under the body of the vehicle, and steering would take place by driving the slider, through self-locking gear-wheels, round the circular segment, so that the forecarriage would be locked to the body in the *horizontal* plane in every position in which it was placed for steering purposes. This method of articulation had previously been referred to in the Proceedings,[1] but more recent investigations had proved that in order to provide in an exact manner for the relative rotation between the forecarriage and body, the pin P, instead of being placed horizontally as there shown, should radiate to the centre of the ball-and-socket joint as above described. The back axle could also be driven by transmitting through the ball-joint, e.g., by electric drive, if an electric or petrol-drive electric motor were used. In this manner each wheel would always be in effective contact with the road and the weight on each would be approximately constant, because the two axles would always be free to take up any angles relatively to each other in the *vertical* plane; and each axle would be driven in the direction in which it was moving at the instant, and so all tendency to force the wheels

[1] Minutes of Proceedings Inst. C.E., vol. clxix, p. 89.

Dr Brightmore. sideways would be obviated. He ventured to suggest that the solution of the corrugation difficulty lay in articulation, so as to maintain an equal load on each wheel, and in driving through both axles.

Mr. Chapman. Mr. H. T. CHAPMAN remarked that road-corrugation was—and would become still more so—an interesting factor in the life of roads and of the vehicles passing over them. He had supervision over large mileages of set-paved roads of various kinds, both with and without concrete foundations, and could not quite agree with Mr. Leeming as to the extent of corrugations on this class of road. In Lancashire at one time very large sets were favoured, but they were discarded when the heavy motor-traffic came in evidence, owing to the tilting and movement of the sets under it. He was of opinion that the best type of granite-set paving consisted of 4-inch cubes on concrete with a sand bed or cushion, and if this were well laid, grouted and racked, he ventured to say that very little corrugation would appear even under intense traffic. He had not experienced much corrugation of Durax paving. The Sidcup section of this paving which was not on concrete had now been in existence $7\frac{1}{2}$ years, and had carried more than 9,000,000 tons of traffic, including frequent motor-bus services, but he could not see much sign of corrugation, although some of the cubes were splintered and shattered. Tar macadam, if properly mixed with suitable materials, did not corrugate much unless laid too thick and over-rolled in the attempt to obtain quick consolidation, and this conclusion was borne out by the Sidcup sections. Asphalt or bitumen surfacing corrugated very slightly if laid on a bituminous base coat, or in what was termed "two-coat work." When it was laid on a smooth concrete surface, there was a tendency to creep and cause waviness as seen in Victoria Street (Westminster) and elsewhere. It was his practice to cross-roll asphalt carpeting work with a hand roller while hot and not to roll it longitudinally until the material had cooled. He had experienced no difficulty in rolling the base coat longitudinally with a heavy roller. Colonel Crompton's three-axle roller was certainly a step in the right direction. Mr. Chapman had under observation some sections of bitumen two-coat work laid 3 years ago, which became slightly wavy within 3 months of being laid, but he could not see that the corrugations had become accentuated under the traffic. The surface was marked by the traffic when the temperature exceeded 70°, but these indentations were smoothed out by the traffic. If concrete surfacing was to be successful it must be of fine concrete and perfectly even, otherwise it would disintegrate under the hammering and abrading action of the steel-tired traffic, and, even at the expense of slight corrugation, some resilience was essential if the surface of any "cemented" road was to withstand quick heavy traffic. Mr. Chapman.

All highway-engineers, and others responsible for the construction and maintenance of roads, were indebted to Mr. Wood for the valuable results of his practical and theoretical investigations. Mr. Chapman also had contended that so-called inferior and unsuitable materials, at one time almost waste products, could, if properly treated and applied, be made to give infinitely better results than the best known road stones, if the latter were not treated and applied in a scientific manner. For example, untreated Kentish ragstone would carry very little traffic without becoming pulverized and disintegrated, and it was also greatly affected by climatic conditions, but if properly treated with tar it formed quite a good surfacing material, and would carry moderate traffic for as much as 7 or 8 years if surface-tarred annually. This had been demonstrated on the London-Folkestone and London-Hastings roads in Kent. The same had been proved to an even greater extent in the case of tarred slag macadam, which was now acknowledged to be among the best surfacing materials in existence. Experimental sections of tarred slag macadam laid at Sidcup in 1911 which had carried more than 8½ million tons of traffic in 7 years, were still in first-class condition. In addition to the actual saving in tractive and haulage effort by the provision and maintenance of even running-surfaces, and the convenience of the users, the life of the roads was extended proportionately, and the saving to the owners and users of vehicles in repair and upkeep costs, and the consequent extended life of the machines was incalculable. This latter fact was not, he thought, sufficiently recognized. Far too little attention had previously been given to the provision of adequate and suitable foundations and drainage, and the reconstruction bill would be vastly increased in consequence. A certain degree of elasticity or resiliency was just as necessary in surfaces and foundations of roads as in other structures, and that was why he favoured a bituminous base coat or bituminous concrete rather than a cement concrete to support and carry a bituminous surface. Further, the strong adhesion between the two in the former case greatly diminished the corrugation or creeping action. Mr. Wood's diagrammatic demonstration of the blows of a wheel passing over an irregular surface proved the necessity of maintaining even surfaces for fast traffic, so as to have as perfect a rolling motion as possible. Mr. Wood showed that the greatest care was required in grading the aggregates and proportioning the matrix in the preparation of any bituminous mixtures, and the relation of the

Mr. Chapman. voids to the percentage of bitumen, having regard to the specific gravities of the materials, was a very important factor. It would add interest to Mr. Wood's Paper if the Author would state the temperatures of the bitumen and aggregates necessary to obtain the results he indicated. Mr. Chapman quite agreed that artificially-made asphalt concrete and surfacing of roads, or what was commonly termed two-coat work, opened out vast probabilities for the reconstruction and upkeep of roads, owing to the fact that the bitumen only needed to be imported, practically all the other ingredients being close to hand in any part of the country. Mr. Wood did not refer to the necessity for lateral support for the surface and base coats of roads, but perhaps this important factor did not affect him so closely, as probably most of his roads were curbed and channelled, which was not the case with most rural roads. All road-work must be done scientifically and systematically, and not by rule of thumb as road-work was executed in former days.

Referring to Mr. Bower's Paper, for ordinary civilian traffic *pavé* roads were to his mind an abomination on which neither man nor beast would travel if they could be avoided. About 20 years ago there were in Lancashire, chiefly in the Fylde district, many miles of road the centre width of which (about 12 feet) was paved with cobbles (mostly brought over as ballast from Ireland), with 3 to 6 feet of ashed roadway on each side. These roads were very uncomfortable for wheeled traffic. It came within Mr. Chapman's duties to reconstruct many miles of these roads, which was done by taking up the cobbles, halving or quartering them according to their size, using the material for foundation as far as it went, and surfacing the full width of the road with granite macadam. The greater portion of the Preston-Blackpool road formerly consisted of *pavé* cobbles. Again, a long length of the Preston–Southport and Preston–Liverpool main roads consisted of grit set-paving, without foundation for part or all of the width; and these were reconstructed, utilizing the broken-up sets for foundation and surfacing with granite macadam. Chalk, of which there is so much in Kent and Sussex, was a very treacherous material in roads, and unless it was kept from the action of wet and frost it was liable to cause considerable trouble. He had seen flint-surfaced roads blow up after frost and the chalk "spue up" like porridge. During the war one of the important coast roads in Kent became absolutely impassable owing to the action of frost and thaw, in consequence of the surface having been cut through to the chalk by traffic. He was at issue with Mr. Bower in regard to mud not rising to the surface of a road by pressure; his experience was the reverse. Mr. Chapman. He had stripped a road crust of good metalling 9 to 12 inches thick on a clay subsoil and found clay intermingled with the stone right to the surface. This assuredly had worked up; it had not been placed near the surface. He had also in mind a newly-constructed road consisting of 4 inches of ashes, 9 inches of hard core, 3 inches of slag, and 3 inches of granite macadam, each layer consolidated separately, on a soft yielding clay subsoil. About 12 months after the road began to be used for traffic the wet clay worked up to the surface in places and portions of the road had to be reconstructed. The chief cause of any class of subsoil working upwards was lack of sub- and surface-water drainage; if the clay, chalk, or other material were dry and compact it would not move. He had constructed many lengths of road on brushwood and fagots, but fortunately had not so far had to carry out "pigstye" work on roads in England.

Mr. Collins. Mr. Arthur E. Collins wished to redirect attention to the propriety of considering the vehicle and the road conjointly. Unreasonable damage was done to the roads by reason of the fact that builders and users of heavy motor-vehicles paid little or no attention to their effect on the roads, with the result that it was impossible with the sums at disposal to make or maintain roads to withstand the action of those vehicles. Great damage was done by using wheels too small in diameter; adding to the width beyond, say, 7 inches to 9 inches, was of no service on good roads if the wheels were not mounted in such a way as to adapt themselves to the roads by bearing with all their widths thereon. Rubber tires met the difficulty to some extent, but they brought other destructive influences into play, due to the spreading of the rubber as each part of the tire rested on the road, and to the reverse action and suction as it left the surface. Again, the higher speeds allowed to rubber-tired as compared with steel-tired vehicles contributed to destruction due to shock. Legislation was required embracing not only roads and vehicles but also the methods of providing funds for adapting roads to increasingly heavy traffic. It was obviously unfair for the increased cost of road construction and maintenance due to the introduction of heavy motor-vehicles on roads, not ordinarily wanted therefor, to fall upon the rates of a small highway district. At the same time, if this new traffic was carried on in accordance with the law, these charges ought not to fall upon the users of heavy motor-vehicles. He was of opinion that where the necessity arose for altering a road and its maintenance to enable it to carry such traffic, the increased charge should be a national one.

Mr. Cotterell. Mr. A. P. I. COTTERELL fully agreed with many of the statements made by the Authors. Others were open to discussion and to some possible difference of conclusion. Mr. Leeming did not seem to have given sufficient weight to the effect of self-propulsion through the rolling surface (the wheels) on the surface rolled upon. He brought forward the analogy of the steam road-roller, and because he found some loose material was pushed forward by the rollers, he came to the conclusion that the action of self-propelled traffic tended to form a road-wave in front of such traffic. The effect upon the road through the propelling rear wheels in the backward direction was not so easily noticed, but Mr. Cotterell submitted that it was of greater importance than the forward motion noticed by Mr. Leeming. It was obvious that the horizontal backward pressure exercised upon the road-surface by a self-propelled vehicle was greater than any forward pressure caused by the same motion. Mr. Leeming realized its importance when the driving-wheel, after leaving the ground, returned to it once more (p. 130), but it was there all the time the vehicle was being propelled. On p. 126, in describing the rolling action and driving action of wheels, Mr. Leeming again noticed the importance of this backward pressure, but came to the curious conclusion in *Fig. 3* that the paving sets developed a movement in the direction of the traffic. Mr. Cotterell was not prepared to say that such movement could not be found, but in the instance given by Mr. Leeming on p. 134, at the bottom of hills, where Mr. Cotterell had certainly noticed the curving of wood blocks, especially on the up-traffic side in the direction of the traffic, he thought the movement could be explained in a different way. When approaching a hill the motor was speeded up on top gear in order, as Mr. Leeming said, to go up without changing gear if possible. The driving-wheels therefore struck the gradient with considerable impact, and it was this pressure that caused the surface to lie down in the direction of the traffic for a short distance. On the other hand, when descending the hill there was very little, if any, driving pressure exerted, whilst the momentum of the motor had it all its own way, and there was thus a corresponding tendency to make the road material lie down in the direction of the down-coming traffic. He had not, however, noticed so much change in the surface on the down as on the up side at the foot of a hill. This factor of the horizontal pressure on the road caused by self-propelled vehicles was, he fully admitted, not by any means overlooked by Mr. Leeming, but it would have considerably illuminated Mr. Leeming's conclusions if it had been taken more fully into account. For instance, the action described by him at the foot of p. 129 would be seen to become much more like that of a horse galloping, and its effect upon the road-surface would correspond with that produced not by one horse, but by many, each striking its hoofs at or near the same spot and kicking up the ground behind it. A self-propelled motor did, in fact, exercise upon the road surface, whilst it was being propelled, a constant pressure throughout the whole circle of rotation instead of intermittently as in the case of horse-drawn traffic. It would, he believed, be a profitable study to follow up the relation between the different kinds of traffic and the harmonic wave that might be caused by them. Most public roads were used by different types of traffic, and the effect of any particular type was therefore likely to be lost. That road-corrugation was due to the pushing up of a heap or ridge—as Mr. Cotterell submitted—by the propulsive action of the vehicle, until it reached a dimension sufficient to resist further movement, seemed to him to be quite true. That it had some relation to the kind of traffic, and that it might be caused by other forms of traffic beside self-propelled rolling surfaces appeared also to be the case. On a gravelled footpath that he used on his way to a station, the surface worked into corrugations with a pitch of about 5 feet. It was constantly doing this after every repair and recoating. There was nothing to account particularly for the formation, and the impression was therefore left that there was some connection between these corrugations and the special use to which the footpath was put. He appreciated the Paper, and would like to add that Mr. Leeming had brought forward a subject that would become of increasing importance as self-propelled heavy motor-traffic came more and more into use. Mr. Cotterell.

Mr. W. H. Delano, as a veteran natural-asphalt expert, suggested that the nomenclature of bituminous and asphaltic products should be rigidly enforced, in order to prevent mistakes in specifications and to avoid tautology. Thus, asphalt was pure carbonate of lime naturally impregnated with pure mineral bitumen. It was not bitumen, it was not pitch, nor gas-tar, nor petroleum residue. Bitumen was mineral pitch. It was not gas-tar, whether soft or inspissated, nor was it tar, or pitch, from the residue of distillation of crude petroleum, shale or fats. In its pure state it was found in asphalt rock; in an impure state in Trinidad, Venezuela, etc. Thus, gas-tar and bituminous pavements were not the same thing. The residue from the distillation of crude petroleum, shale and Trinidad bituminous oils, was used for consolidating the surface of macadam chiefly in the United States; its binding effect was greater and Mr. Delano.

Mr. Delano. more lasting than that of gas-tar. With regard to waves or corrugations in compressed asphalt roadways, his experience was that they generally occurred owing to solar heat on too rich asphalt surfaces and could be overcome by blending the rock and grinding it fine. It had been found that depressions would occur even where 8- or 9-inch Portland-cement concretes were the foundation, the cause being deep subterranean streams or springs causing a slight flow of the superjacent solids.

Mr. Dryland. Mr. ALFRED DRYLAND considered that Mr. Leeming's Paper served a very useful purpose in directing attention to what he had for long felt to be the most important phase of the road question, namely, the deforming action of vehicles upon road-surfaces. The figures given by Mr. Wood, showing the wear of wood paving under a large traffic to amount to only 1 inch in 35 years, illustrated a view he had frequently expressed that the deterioration of road-surfaces by simple attrition was not the most serious factor in the case. If destruction came only from attritional wear there would be no reason why wood paving should not last for 35 years; yet the normal life was only about one-third of that period. The fact was that deformation of surfaces, in the shape of trench-openings, waves, and corrugations, and consequent destructive blows, reduced the life by more than one-half. In Mr. Dryland's experience it had been a very rare event in recent years to have to resurface a road because of a surface worn out by attrition; it was always because the irregularities had become so great as to render the travel of vehicles uneven, and therefore both uncomfortable and destructive. For these reasons he did not attach great importance to mere measurements of wear in thickness of coatings. Measurements on the Sidcup trial lengths had proved that temperature-changes must be taken into account; in some instances it was found that the road-surface had grown by an inch after some months wear. It was obvious that any measurements of wear could only be comparative if taken at the same temperature, but the data obtained also showed that surface movements both transversely and longitudinally vitiated the results as recording any definite wear. Mr. Leeming's investigations into the movements of self-propelled vehicles and the effect of the present method of springing opened up possibilities in the direction of the discovery of improvements which Mr. Dryland thought might be pursued with advantage. He suggested an exhaustive scientific investigation into the effect of methods of propulsion and springing of vehicles on the action of wheels upon all kinds of road surfaces, under all conditions of weather and temperature. Such an investigation, if sufficiently thorough and prolonged, might lead to discoveries which would save very large sums of money in road-maintenance. Mr. Dryland.

With regard to Mr. Wood's theories as to the thickness of film-coatings, and the conclusions he drew from comparisons between "synthetic" and natural asphalt, Mr. Dryland suggested that Mr. Wood's inferences should not be accepted without much more conclusive reasons than were furnished. The method of computing surface areas appeared to him to savour too much of the nature of assumptions, which might well be erroneous, and if so destroy the accuracy of his calculations of film-thickness. It also seemed to him rather futile to compare film-thickness as between an agglomeration of impregnated particles in the case of natural asphalt and a surface coating on particles incapable of impregnation by an added matrix. The inference Mr. Wood appeared to suggest was a reduction in the quantity of bitumen in "synthetic" mixtures—a dangerous suggestion, as almost all the failures which had been experienced with this material arose from insufficiency of bitumen. When it was considered that the aggregate of "synthetic" asphalt consisted of sand and fine dust, materials which by themselves had little value in road-surfacing, it seemed unwise to suggest the curtailment of the one material, the bitumen, which gave it value as a weather- and attrition-resisting medium. The fact that in the most successful practice it had been found desirable to increase the quantity of the finest grade of material, in order to make it possible to carry a larger proportion of bitumen, was a strong argument against Mr. Wood's suggestions. It was noticeable, however, that in his conclusions Mr. Wood adopted grading which was in general accord with recent standard practice.

Mr. John C. Fergusson remarked that one of the clearest examples, in his experience, of road-waves or corrugation formed by motor-omnibus traffic, occurred about 6 years ago on the Harborne Hill road, Birmingham. This road had been used many years by horse omnibuses and other horse-drawn vehicles without showing corrugation. Very soon after the motor-omnibuses started running between Birmingham and Harborne, there appeared two or three distinct "waves," which started from a hole in the roadway near the top of the hill, and gradually extended, in the same formation to the bottom of the hill and even along the level roadway beyond. The corrugations were 12 to 14 feet apart and 6 to 8 inches deep; the width between them seemed to increase on the steeper portions of the road. After a time the appearance of the road-surface resembled an old logging road from which the skid-logs had been drawn, and it was alarming to watch a motor-bus jolting down Mr. Fergusson.

Mr. Fergusson. the hill, over this wave formation, often with its front wheels in the air. Much useful knowledge on the subject might be obtained by a study of the particular vehicles which had caused this damage to the road, as the swaying and jolting motions of vehicles varied according to the style of their suspension, their loading, and particularly the length of their wheel-base. The famous Cobbs' mail-coaches of old colonial days were suspended lengthwise on leather straps and had a short wheel-base; these coaches with four or six horses attached to them were driven rapidly over very rough ground where a wagon with steel springs would not last long. The first cause of road-corrugation might fairly be ascribed to some hole or break in the surface of the road which had arrested the free motion of every running vehicle that passed over it, for it was at this point that the process of corrugation invariably began. In his opinion the smooth waterproof road-surface was of greater value than a hard-core foundation. Some of the roads around Southampton, formed of gravel rolled and sprayed with tar, had lasted well under very heavy motor-lorry traffic during the war. With regard to the movement of the road-bed, causing a tilting of the stone sets and wood blocks, he had had to take up miles of stone sets for the construction of electric tramways in the Midlands. These sets had been laid for 17 years and had been subjected to very heavy steam-traction traffic in the Black Country; yet he had never observed a single case of tilting of stone sets either upon the level or upon inclines, although some of the stone sets were worn down to half their original depth. Stone sets were more inclined to rise in twos and threes and small bunches when they became loose. With wood blocks, tilting was not uncommon. In the Hagley Road, Edgbaston, on both sides of the tramway the wooden blocks had had to be taken up and relaid, because they had been tilted in the direction of the traffic, thus supporting Mr. Leeming's statement. The tilting of the Hagley Road wood sets might have been partly due to the blocks having been laid on a very smooth hand-finished concrete foundation. Mr. Leeming's statement that soft-wood blocks lasted longer than hard ones did not agree with the general opinion held on this subject; the Government allowed a grant for 15 years on the life of hardwood blocks and only 7 years on soft-wood blocks. The softer and lighter individual wood blocks in a paved road always seemed to wear out before the others, and had to be renewed.

Mr. Hooley. Mr. E. Purnell Hooley considered that Mr. Leeming's Paper read more like that of an observer than of a practical road-maker. He certainly disagreed with the statement that waves were most noticeable in the wear of macadam and tar macadam roads. Mr. Leeming's mind would be quickly disabused of this view, could he but see the New Road and Banbury Road, Oxford, constructed with a "carpeting" of asphalt. A journey in a car with powerful head-lights showed waves to perfection, and in the early days of motoring they appeared greater even than at the present time; this went far to prove, to Mr. Hooley's mind, that waves were not entirely the effect of quick or heavy self-propelled traffic, as was so often suggested. In his opinion there was little doubt that serious road-waves were but too often the result of the unskilled experiments of theorizing road-makers. If a road were properly constructed with a perfect base and foundation, a substantial sub-crust according to the traffic the road would be called upon to bear, and a minimum thickness of 4 inches of good permanent wearing surface, the whole being suitably secured together and properly maintained (not allowing the surface to wear down until it was too thin to stand even cycle traffic), there would be no complaints as to waves or theorizing as to their cause. Mr. Hooley.

With regard to Mr. Wood's Paper, did the Author intend to lay down generally that 6 inches of concrete was good in any case? Mr. Hooley's personal experience was that less than 9 inches of concrete was useless within 18 inches of any road-surface. Would the Author recommend concrete for county-road construction, or for use in colliery districts, where it was often necessary to open roads for sewer-, gas-, water-, and electric-light breakages, in as many as a hundred places per mile in the course of 12 months? It should be made clear that the Paper, which was a useful one, related to town traffic on town roads; if read as applying to country roads, it might do harm to those who had to labour under difficulties unknown to town engineers. He would be glad if the Author would be good enough to state the full thickness of the artificial asphalt road, mentioned in the "conclusion," that could be laid for 4*s*. 6*d*. per square yard. Was it for the 1 inch to $1\frac{1}{4}$ inch mentioned, for "carpeting," or was it for the full 4 inches or $4\frac{1}{4}$ inches of the two thicknesses, and where if the latter, could such be seen? Had it been found that such a surfaced road was wavy?

He was unable to gather whether Mr. Bower's Paper had been written with the idea of helping ordinary road-surveyors in the management of British roads, or as a guide to future campaigners. If the former, it was to be hoped the roads would never have to carry military traffic, and be "relaid"—or perhaps "reconstructed" would be a more suitable term? In England roads were constructed for the ordinary amount of traffic they were called upon to bear, and were of reasonable width. Did the Author suggest that an ordinary 18-foot country main road costing, say, £100 per annum per mile to maintain, should be widened, and thus cost about

Mr. Hooley. £270 to maintain, because some day the country might be invaded and the roads called upon to carry military traffic? Theorizing as to the width of roads too often caused lay members of local councils to cross swords with their technical advisers, and such Papers as this were cited, as if adapted for general application. Had the Author ever tried packing the foundation stones at an angle of about 45° to the traffic, instead of parallel to the traffic. If not, he might have found a road greatly improved by such a plan, for obvious reasons. Mr. Hooley did not agree that no water should be allowed in the hole that was to be patched, if by this the Author meant that no water was to be used at all. "Dry" patches meant loose stone kicking about. He presumed that *Figs. 4* (p. 164) illustrated merely a temporary method of holding up a road; surely there should be additional buttressing. The corduroy road would be less inconvenient if the timber were laid at an angle of 45° to the traffic, which would go far to remove the nuisance of bumping. It was unfortunately the fact, that an improvement in construction was rarely appreciated at its real value by the powers. Things went on in the same happy-go-lucky manner, and too often Papers read recommended the same old rut or led to it, while if a reasonable suggestion was offered, which was not designed by a "power," it was turned down without being experimented upon. The Author's remarks under the heading "General," Mr. Hooley would prefer to put in the following terms:—No road should ever be constructed without good drainage. Carelessness should never be allowed. Soling rock should always be laid at an angle of 45° to the traffic.

Mr. Jackson. Mr. HARRY JACKSON considered that The Institution was to be congratulated upon the receipt of these Papers, which followed in sequence the earlier Papers [1] on Creep of Rails, the Paper [2] on road problems by Mr. Mallock, and earlier discussions on the corrugation of tram-rails. Such Papers showed the advantage accruing to the profession by the expression of individual experience, and it was to be hoped that, at a not far distant future, discussion of these and other Papers at Local Associations of The Institution might take place.

The chief problem dealt with in the Papers was the old one of a surface subject to a rolling load. Mr. Bower expressed the opinion that no mud rose to the surface by pressure from above. He said: "The true cause of mud formation is the poor quality of the material used . . . which, by attrition through some inches of

[1] Minutes of Proceedings Inst. C.E., vol. ccv, p. 227.
[2] *Ibid.*, vol. clxxviii, p. 120.

depth, forms the mud, while destroying the surface." It would appear that he referred there to surface attrition. Mr. Wood said: "Internal grinding is responsible for about 80 per cent. of the cost of road-maintenance"; and on page 149: "It was found later that, although the granite of the mixture had not worn, for some reason the material had disintegrated, especially where the traffic was concentrated." It was clear that there were two distinct operations of wear taking place: (*a*) Attrition due to the frictional resistance between the wheel and the road-surface. (*b*) Internal attrition between the particles forming the body of the road-structure. The relative magnitudes of these two actions could be gauged by the particulars given in Mr. Wood's Paper as to material scavenged from the streets. Taking the attrition of soft-wood pavements as being 0·007 inch, comparing it with the mud formed on the roads in Fulham during 1906–7, and assuming that this mud was produced out of 6-inch macadam, it would be seen that Mr. Jackson.

$$\frac{\text{Mud due to attrition of surface}}{\text{Mud due to internal grinding}} = \frac{0{\cdot}007}{0{\cdot}083} = \frac{1}{12}$$

In earlier discussions at the Institution Mr. Jackson had referred to the wave action which was transmitted along any surface subject to a rolling load. In the case of a railway of sleeper construction, the velocity of the wave along the road appeared to be such that the crest of the wave advanced in front of the rolling load. Corrugation was but rarely produced, whilst there was invariably a creep of the rails. In the case of tramways, the wave did not travel at such a rate as to cause the crest to be always in front of the rolling load. The wheel jumped the crest, and when the periodic time of the wheel-jump approximated to the periodic time of the wave, corrugation of the surface ensued. In the case of road-surfaces, such as those discussed in the three Papers before the meeting, this wave-action evidently proceeded. The energy of the wave-motion was destroyed by disintegration of the granite, etc., forming the top layer of the road. That this wave-action was of considerable amount was proved by the fact that the mud produced by its action was twelve times that produced by attrition on the surface. It seemed clear, therefore, that, given first of all a structure which would distribute the load coming upon it, over the surface of the ground, in such a way as not to cause fracture of the structure or permanent displacement of its constituent parts, there would be this wave-action, which must be provided for. It was particularly interesting to note that the effects of creep and corrugation were both evidenced in a road subject to heavy fast-running traffic. It might be well to set out a statement of the particular

Mr. Jackson. kinds of roads mentioned by Mr. Leeming in the order of their tendency to corrugate :—

	Page.
(*a*) Water-bound macadam roads	141
(*b*) Tar macadam roads	142
(*c*) Granite sets on yielding foundation	140
(*d*) Durax paving	140
(*e*) Hardwood blocks	140
(*f*) Granite sets on sand cushion	140
Cement-grouted granite set on concrete	140
Soft wood on concrete	140

It would be observed that soft wood came in the last batch. The reason for this would appear to be that, in the first place, the concrete foundation was quite sufficient to take up all the loads, apart from the wave-action; and in the second place, that the wood, as laid, was able to damp down the wave-action by elastic deformation rather than by disintegration and attrition of its parts. It could not be too strongly emphasized that any road-formation which had to carry heavy fast-running traffic must provide for these two requirements—static support and transformation of wave-energy. It would appear that a road-formation which confined the wave-action to a definite upper part of the structure was the most satisfactory.

Mr. Wood's Paper dealt most with the effort to produce an upper portion of the road-formation. His experiments led him in the direction of a material devoid of plasticity which, whilst sufficiently rigid to prevent deformation of this surface under the static load, was yet elastic or resilient enough to take up wave-action without attrition of its constituents parts. It appeared from Mr. Wood's Paper that natural asphalt, of the Val de Travers type, was best fitted for this. He was to be congratulated on the near approximation of his artificial asphalt to the ideal material.

From Mr. Leeming's very ingenious analysis (pp. 127–129) of the action and reaction between the wheel and road surface, it would appear that the acceleration he had introduced in the expression

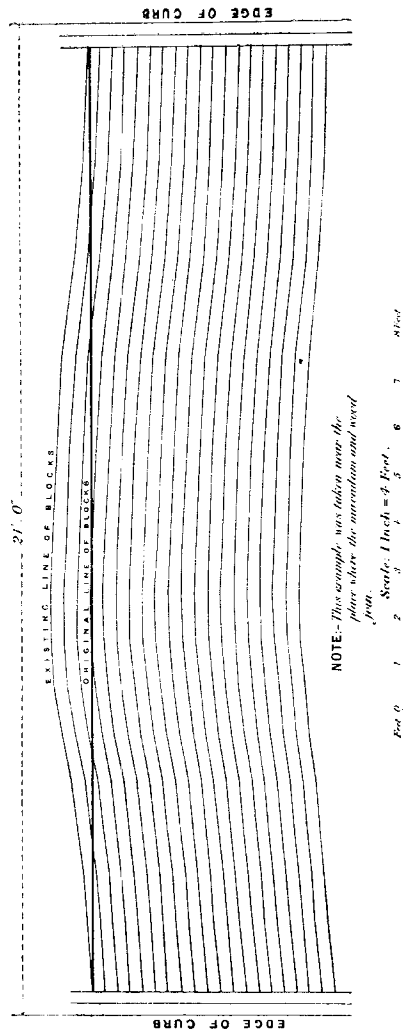
$$P = \frac{W}{G} \times \text{acceleration}$$

was not in the same direction as the velocity V given on the previous line. It was possible that his assumption in paragraph (*a*), that p/r was a definite relationship might be tested by examination of a number of tramways which had wheels of different diameters running on them, the diameter for any one system being constant. Unfortunately Mr. Leeming did not indicate anywhere in his

Mr. Jackson.

Paper the pitch of the corrugations of the particular kind of roadways, nor did he differentiate between corrugation proper and irregularity of surface caused by the heaping up of plastic material, particularly at stopping-places of motor-omnibuses. In the case of corrugations proper, as distinct from heapings of plastic material, even if the blow caused by the wheel was small, the cumulative effect might be large. If the blow occurred at regular intervals coinciding with the periodic time of the wave in the road-material, the amplitude of the wave in the road-substance (that was the up and down movements of the particles) would be gradually increased, as was the case in the sympathetic vibrations of piano strings. When, in an elastic material this amount of deformation (strain) exceeded the strain at the elastic limit of the material, permanent corrugation would result. The determining factors in this were: the velocity of the traffic at which corrugation occurred, and the velocity of transmission of an impulse through the material. The experimental determination of these two factors would, in Mr. Jackson's judgment, lead to a scientific solution of the road-corrugation

Fig. 2.



Plan showing Movement of Wood-Block Pavement in King Street, Cambridge.

Mr. Jackson. problem. It very often happened in natural phenomena of a very diverse order, that the same physical cause was producing widely different results. The rolling of road surfaces was a case in point. Only by careful survey and investigation of all the different kinds of surface rolling action were engineers likely to solve the problem of a good road-surface for heavy motor-traffic.

Mr. Julian. Mr. JULIAN JULIAN, of Cambridge, submitted a drawing (*Fig. 2*) representing the actual movement of wood paving in a Cambridge street, noted by him in 1915. The road had no longitudinal gradient, the camber was slight, and the paving was of hardwood 3 inches deep on about 8 inches of concrete. He had no census of the traffic, but imagined it would be about 600 motors and horse-drawn vehicles in 12 hours. It would be noticed that the movement was almost entirely in one direction, while the traffic must be about equal in the two directions. He was of opinion that where the movement was mainly influenced by the direction of traffic, it was in the opposite direction to that shown in Mr. Leeming's diagram. In other words, the sets moved in the direction of the lower half of the wheels, but in many cases, especially with wood blocks, the movement was influenced by other causes than the direction of the traffic. In wood paving, expansion produced severe stress, and then a very slight accidental condition, it might be gradient, or traffic, or even a manhole-cover, was sufficient to determine which way the stressed blocks would move.

Mr. Leitch. Mr. D. C. LEITCH remarked that the figures given by Mr. Wood regarding loads on foundations, pp. 144, 145, appeared to require some further explanation. No doubt cases could be cited where weak subsoils had carried loads, in deep foundations, equal to or greater than the $\frac{1}{16}$ ton per square inch referred to by the Author. But the foundations now in question were of trifling depth, so that displacement of the ground, under very moderate pressures, readily occurred. The width of track of a 10-ton roller was usually about 6 feet; the Author said that the intensity of pressure was much more than $\frac{1}{16}$ ton per square inch. But, even this corresponded to a length of bearing on the subsoil of about $2\frac{1}{4}$ inches, and a compression of about $\frac{1}{40}$ inch. With a load of 4 tons per foot of support—about as much as any subsoil not rock could be expected to support on its surface—the length of bearing would be 5 inches, and the compression about $\frac{1}{8}$ inch. This method of testing subsoil seemed not very reliable; a small difference in compression under the tires, which could hardly be measured with accuracy, corresponded with a large difference in intensity of load. It was also hardly possible to measure the length of the prints made by the tires, as the roller was run into position for the test. The Mr. Leitch. relation of the hypothetical load of 5 tons per square inch (p. 144) to conditions such as occurred in practice was not very apparent; such a load would destroy any road surface, except perhaps one of granite blocks. The distribution of heavy wheel-loads was effected, in the case of more or less elastic road-surfaces, by compression under the wheel as it passed. Rigid road-surfaces such as granite consisted of blocks which were usually about 4 inches in width, and served to distribute the load. In the case taken by the Author, a 10-ton roller, the weight on a granite pavement would be distributed over about 6 feet by 4 inches or 2 square feet. This gave 5 tons per square foot on the concrete below. With the roller on an elastic surface, such as asphalt on concrete, or macadam 4 inches thick, and allowing for a length of bearing, below tires, of 2 inches only, the load would be distributed over 6 feet by 10 inches, or 5 square feet. In this case the intensity of the pressure on the subsoil would be 2 tons per square foot. These figures, like the Author's, made no allowance for the very considerable stresses due to impact, which could hardly be estimated. It was suggested that 2 tons per square foot, static load, was as much as any subsoil, not being rock, could be expected to support in road foundations. The Author's conclusion that bitumen expanded $\frac{1}{500}$ of its bulk, per 10° F., was noteworthy, because there was no other substance, solid at ordinary temperatures, which had a coefficient of expansion approaching this. Accepting this figure, it was evident that the linear not the cubical expansion was in question, and this was only about $\frac{1}{1500}$ per 10°, so that the increase in thickness of a 2 inch layer, due to a change of 82° F. in temperature, was not $\frac{1}{150}$ inch, but $\frac{8\cdot 2 \times 2 \times 0\cdot 21}{1500} = 0\cdot 0023$ inch. From this should be deducted the expansion of the aggregate, say, 0·00065 inch, leaving 0·00165 inch. This would equal only three bituminous films of 0·0005 inch which the Author considered a moderate thickness. It was not clear why the difference in coefficient of expansion, between the bitumen and the aggregate, should cause disintegration. The mixture when laid was much hotter than at any subsequent time; and the passage of traffic tended to consolidate it and to close any minute fissures due to unequal expansion. Was it not possible that the disintegration observed was due to deterioration of the bitumen? Reducing the size of the aggregate, as recommended by the Author, might be in some respects beneficial; but it had the disadvantage of increasing the percentage of voids to be filled with bitumen, and rendered the road-surface more likely to sustain injury from the

Mr Leitch. blows of iron tires and the suction of rubber ones. Stones of medium size were less easily plucked out or knocked out than were the small ones recommended.

Mr. Marriott. Mr. T. G. MARRIOTT considered that Mr. Wood's Paper was of interest as being an effort to direct attention to the technical side of asphalt construction. Some of the Author's conclusions were clearly open to objection. His theory as to the failure of asphalt macadam mixtures being caused by the contraction of the bitumen was not fairly supported by the extreme range of temperature which he cited, namely, a difference of 82° F. Such a range was rare in this country and could only occur during the summer. It was agreed that failure in this class of work only occurred during the winter months, when no such variation took place. Assuming that such contraction as Mr. Wood mentioned did occur—and this could only be in summer—the "coefficient of restitution" of the bitumen would be ample to allow the pavement to recover, especially having regard to the soft consistency of the bitumen used, and the effect of subsequent traffic during warm weather. In Mr. Marriott's opinion the cause of this particular failure was to be found in the fact that the Author had exposed a mixture containing large particles such as $1\frac{1}{2}$-inch granite to a density of traffic which was beyond the capacity of this form of construction. It had been clearly proved in America, where this mixture was laid extensively, that it was only successful under light traffic. Heavy traffic in cold weather set up vibration in the larger fragments and resulted in the admission of water to the pavement and consequent disintegration. Mr. Wood's mathematical deductions as to film-thickness were untenable, seeing that he based them upon an impossible assumption, namely, that the particles in paving mixtures were cubes. Obviously this was not the case where sand and pulverized materials formed the aggregate. His comparison of the film-thickness of sand mixtures with those of natural rock asphalt was inadmissible seeing that the latter was composed of rock saturated or impregnated with bitumen. There was therefore no true analogy between the two forms of mixture. The suggestion that the artificially prepared composition should or could be adapted by improved machinery, so as to follow the lines of the natural rock, was quite extravagant when it was remembered that the rock asphalt formations resulted from upheavals of Nature during early geological eras, and thousands of years had elapsed since the bitumen was forced into the rock—probably in the form of vapour—while modern artificially-mixed asphalt was obtained by mechanically imparting a film of bitumen to impervious sand particles at the rate of 20 or 30 tons per hour. Any attempt to reduce the percentage of bitumen in this type of asphalt to that of rock asphalt would be doomed to failure. The theory of artificial asphalt was to reinforce by means of "filler" or "dust" the natural bitumens, such as Trinidad, and by this means form an elastic cushion between each of the sand-particles of the aggregate. It would be seen from the figures which Mr. Wood quoted that his statement that rock asphalt employed only half the amount of bitumen which was used in artificial asphalt was untrue, and was based on the assumption that both mixtures consisted of films of bitumen surrounding particles, which was only strictly correct in the case of machine-mixed asphalts. There were many other points in Mr. Wood's Paper which Mr. Marriott would have liked to challenge had space permitted. A protest, however, must be entered against the statement on p. 156 that practically any aggregate could be used in asphalt construction. Frequent failures occurred as the result of this supposition that any inorganic rubbish could be used in asphalt processes. The technology of building stones was probably the most useful study which engineers could pursue in connection with this question. Briefly, his view, based on considerable experience, was that the modern asphalt mixture was the result of many factors and causes, the absence of any one of which might be the cause of failure, though all the others were present. Mr. Marriott.

Mr. W. O. E. Meade-King observed that owing to the War, road transport had been very much to the fore, and probably would be even more so; therefore road construction and maintenance called for the earnest attention of engineers. After the able manner in which the subject had been dealt with by the Authors, it would almost seem as if there was little to be said; but there were one or two matters which appeared to be worthy of further consideration. Mr. Meade-King.

Mr. Bower said that no road should be less than 24 feet wide, and if possible it should be 30 feet wide. That was the width of the roads in the days of the grandfathers of the present generation, since which time traffic had increased a hundredfold, but the roads had remained the same, the consequence being that certain parts of a road got more than their fair share of traffic. It might sound out of all reason, but he believed the day was sure to come when all main roads would be 60 feet wide, and the sooner that day came the better it would be for the roads. The first cost, of course, would be heavy, but the maintenance, if the roads were properly constructed in the first instance, would be lighter. As to drainage, Mr. Meade-King. and its necessity, probably all were agreed, but the camber of a road should be no more than was just sufficient to carry off the surface water; it was a common thing to see a 24-foot road with a camber of about 1 in 20, the result being that vehicles of all sorts used the centre of the road except when two vehicles were actually passing one another. A camber of 1 in 50 would be sufficient for drainage, and there would not then be this tendency to use one part of the road only. Again, rolling by steam roller, could be, and often was, overdone, both in regard to the weight of the roller and the extent to which it was used. A 10-ton roller was probably the heaviest that should be used, and it was a question whether an 8-ton roller would not be better; as it was, roads were to be seen, made of all sorts of material, instead of granite, as they should be, rolled and watered till the surface resembled pea-soup, all of which after a few days of fine weather resolved itself into dust. The whole substance of the road had been destroyed in the making. As in all other work, the foundations were the most important part, and in his opinion nothing could beat the usual hand-packed stone, set on edge; this was generally steam rolled, and then the next layer of material was put on and rolled, and so on; but if the hand-packed foundation, before being rolled, were blinded and grouted either with tar or cement and then rolled before the grouting had begun to set, a much better foundation would be obtained, on which the weight of passing vehicles would be more evenly distributed. These remarks were intended to apply to the main country roads, and not to streets in towns where wood paving, granite sets, etc., were in use.

Mr Read. Mr. R. Read, after 60 years of busy professional life in London, Manchester, Salford, and Gloucester, during which, among other work, he had had a good deal to do with road construction and maintenance, was still strongly of opinion that Telford's maxim, arrived at during the construction of the main road from Chester to Holyhead, still held good, namely, "The real strength of a road is in its foundation." Telford invariably strengthened all weak places, especially those having a clay subsoil, with a hand-pitched foundation of rough block stone to distribute the weight of the traffic. Unfortunately his contemporaries and successors (excepting McNiell in Scotland) did not follow this excellent example, and hundreds of miles of roads in England were constructed by laying down successive coats of macadam from the nearest quarries on the natural foundations, whatever they might be. This was probably done to save first cost, but as a road from one town to another passed over various geological formations and kinds of subsoil, every change in the strength of the foundation provided a starting-point for corrugation of the road-surface. Until about 1875 these layers of macadam had to be consolidated by the traffic itself, but the advent of the steam-roller about that date brought about an immense improvement. In 1878 Mr. Read introduced the steam-roller into Gloucester, and also the use of the Clee Hill Dhu stone (basalt) in preference to local limestone from Chepstow and Bristol, thereby reducing the scavenging to one-third of its previous quantity. The great cause of corrugation in town roads was that, in addition to the variations of the natural foundations, every road had longitudinally a sewer, a water-main, and a gas-main, not to mention electric cables, etc., running through it, and transversely the house services to and from all of them. The trenches for all these pipes were sources of weakness to the road, so that it was almost impossible to get a uniform strength of foundation; consequently corrugation was bound to occur with heavy loads and fast traffic, because however well a trench was filled in and rammed—and the ordinary workman was not fond of the rammer—any trench was a source of weakness for 20 years or more. Mr. Read.

Mr. Leeming's calculations and experiments on the dynamic effects, both on the road and on the self-propelled vehicles, of passing over corrugations at various speeds were very useful and interesting, and the same remark applied to Mr. Wood's diagrams of the effects of a car passing over a depression at various speeds. Unfortunately, the better a road was for self-propelled vehicles, the worse foothold it gave for horses; but it appeared to be quite probable that these animals would in the near future be crowded out of towns. Mr. Wood's experiments showing the differences in percentage by weight and by volume, and the expansion of bitumen by heating, were very useful and instructive, and seemed to show that granite and basalt required and absorbed much less bitumen than slag; this accounted for the apparent failure in some cases of tarred granite as compared with tarred slag when equal quantities of tar were used. Mr. Read was afraid Mr. Wood's elaborate calculations, to five places of decimals of the thickness of the film of bitumen on aggregates, were rather a waste of time, and it was also somewhat difficult to understand from the figures given in his experiments on the "Effect of grading on weight and solidity" (p. 154), how he arrived at the conclusion that these tests brought out the fact that the smaller the aggregate the greater the voids. So much depended on the way the gauge-boxes were filled and the amount of ramming, if any, in each case. Mr. Read was certainly under the impression

Mr. Read. that the smaller the aggregate (other things being equal) the less the voids.

Mr. Bower's Paper showed the difficulties the Royal Engineers had had to deal with in repairing the roads of France during the War with any materials they could lay hands upon. As the corduroy road was in two sections, if a shell dropped on one side of the road there was still a chance of the other half remaining intact.

Mr. Walters. Mr. R. C. SKYRING WALTERS observed, with reference to Mr. Bower's Paper, that it was certain that carelessly-formed bottoms were the cause of endless trouble. As an example, he might mention a 1-inch tarmac floor, covering 1 acre, laid on 6 inches of slag concrete. This was put down on a works "tip" consisting of 20 feet of ashes, made up during the previous 10 years. The whole was well rolled with a 10-ton roller, and it subsided by *varying* amounts up to 2 feet. The 6 inches of concrete was put down, and within a fortnight heavy goods-traffic (railway) and other heavy loads, such as a crane weighing 20 tons, passed over the site for constructional purposes. Only one or two slight cracks appeared in the virtually green concrete. With regard to the packing of soling pieces transverse to the direction of traffic, there should be no objection to this method if the packing were done tightly on a rolled bottom of uniform bearing-capacity; the laying of the long side in the direction of the traffic seemed to present difficulties (not the least being the objections of the English navvy ganger) for country roads, where there were no rigid curbs to work on, to keep the stone upright. Presumably the soling was started from the centre of the road, and was worked to each side simultaneously. With regard to Mr. Bower's view that mud-formation was due entirely to attrition, this certainly seemed to be borne out at Yate, Gloucestershire, where there was to be seen Carboniferous limestone giving a grey mud, adjoining patches of soft Pennant sandstone giving a red mud (identical with wetted dust from a crusher), the sub-soil in both cases being an orange yellow clay.

Mr. Wood. Mr. FRANCIS WOOD, referring to Mr. Leeming's Paper, remarked that, whatever the theory of the cause of corrugations or waves, they were undoubtedly the result of two agents, the vehicle and the road structure. There was little likelihood that the vehicle would be or could be altered to reduce seriously the effect, and with regard to the structure, it must be admitted that waves appeared more prominently on water-bound macadam roads. This form of road structure was admittedly weak, unstable, and unsatisfactory, and if it could be put aside the question of road-corrugation would not call for serious attention, as in other forms of road structures it was of minor importance. Mr. Leeming mentioned set paving as being subjected to corrugations, and it might be gathered from the Paper that they were serious: Mr. Wood had not been impressed by the corrugations in set paving, nor had he noticed the S curves or tilting of the sets. Mr. Leeming seemed to hold the opinion that set paving in general (p. 139) was laid on a yielding bed; if set paving were so laid, one would naturally expect peculiar results. Set paving was almost invariably laid on a stable and unyielding foundation, and as no movement was noticeable (as Mr. Leeming admitted) on such a foundation, there did not appear to be any necessity for a change in the form of the sets. The S curve was noticeable in wood-block paving, but only where the blocks had been laid direct on concrete without any intervening tar or pitch. The extent of the movement was very limited, and the blocks were not tilted, the movement ceasing after the first 2 or 3 years, and these facts, together with the one that no movement occurred in wood paving which was so grouted with pitch that it got right down to the concrete, indicated that the force exerted by the traffic was exceedingly small and could be easily counteracted. In bituminous surfaces there were slight waves and corrugations. They did not occur in the winter, but were apparently formed in the hot temperatures of the summer. The heat softened the bitumen in the top thicknesses of the surface layer, and the force which was sufficient to push the wood blocks forward was just sufficient to push the layer or layers from their original positions. As the hot temperatures lasted only for a short time in the day, the progress forward was limited, but it was sufficient to cause these slight irregularities. The same bitumen, of different consistency, used with a similar aggregate after 4 to 7 years had not developed waves or corrugations except to an infinitesimal extent, and hence it seemed to be merely a matter of adjustment of the consistency of the bitumen employed. Contrary to Mr. Leeming's view, there seemed to be evidence that the bitumen should be increased, not diminished, or it might be that it should be filled to a greater extent with filler dust which, in effect, meant an increase in the bitumen contents. The corrugations would not appear as the road structure improved; but he did not attribute corrugations to motor-buses as such, and he had already pointed out (p. 189) the relative effects of motor-buses and other heavy motor traffic in damaging the roads. In Fulham about 500 to 600 taxicabs running daily to and from a garage on three waterbound roads quickly caused corrugations similar to those complained of elsewhere as due to other vehicles. Mr. Wood.

Mr. Worrall. Mr. ERNEST WORRALL, while in general agreement with most that Mr. Leeming submitted in his Paper, pointed out that at p. 126, under "Traction" the measure rather than the "value" of that resistance to traffic would, perhaps, better express what was intended; and that while under low temperatures waterbound macadam required a higher tractive effort than tar macadam, some experiments carried out by Mr. J. Walker Smith, M. Inst. C.E., and tabulated in his book on "Tar Macadam," published in 1909, showed that with heavier vehicles and higher temperatures the tractive effort on tar macadam was considerably higher than on waterbound road-metal. There would appear to be some inconsistency between the Author's belief in the absence of corrugation in granite sets on concrete with a sand cushion and in wood blocks laid under the same conditions. The greater durability of soft-wood as compared with hard-wood blocks was further evidence of the importance of resilience in enabling recovery from the strains of heavy traffic, mentioned at the foot of p. 142.

Mr. Leeming. Mr. LEEMING, in reply, remarked that he was glad to note the general agreement as to the necessity of considering the subject from the points of view of both the design of vehicles and the construction of roads. Concrete roads, as mentioned by Mr. Boulnois, certainly offered possibilities in the direction of a rigid and wave-resisting surface.

He was particularly interested in the suggestions of Dr. Brightmore, and was in entire agreement with him that the principal solution of the wave trouble lay in driving through both axles, and maintaining so far as possible equal loading on the wheels. Moreover, by electric driving it was possible to have trailer wheels, also driven independently by electric motors, so that there would be less objection to this class of vehicle on the road. Some experiments, as suggested by Mr. Cotterell, Mr. Dryland, and Mr. Jackson, with a view to determine the relative effect of back-axle driving and two-axle driving, and also of obtaining better suspension of the vehicle, would be of very great value.

With regard to Mr. Jackson's point as to the pitch of the waves, there was no doubt that it could be determined if speed, type, and wheel-base of vehicle, diameter of wheels, and direction and depth of the wave compared with pitch, were considered: the variation of the pitch even at short intervals on a road was sufficient to show the difficulty of obtaining a satisfactory result in practice.

He did not agree with Mr. Wood in the opinion that there was little likelihood of vehicles being altered seriously to reduce the effect on the road. The damage done by motor-buses was certainly due to repetition of the type of vehicle and wheel-base, and particularly to back-axle driving; and owing to the preponderance of the motor-bus over any other type of vehicle on the road, corrugation was rapidly set up. Mr. Leeming.

Mr. Worrall raised an interesting point in mentioning the difference of tractive effort in winter and summer on macadam and tar-macadam roads. As other writers have pointed out, this was important as it proved that waviness, on tar-macadam for example, was more likely to occur in the summer than in the winter.

Mr. Wood, in reply, remarked that Mr. Dryland and Mr. Marriott were in apparent agreement that the theories were futile and untenable, and that there was no true analogy between "impregnated" particles in the case of natural asphalt and the artifically-made sand mixtures. It had been customary in the past to think of natural asphalt as carbonate of lime impregnated with bitumen, but just as it was impossible to impregnate a piece of quartz for the reason that it was a solid (free from voids) so it was similarly impossible to impregnate particles of limestone in their finite state. Even if it were possible, the bitumen impregnated into the interior of the particle lost its value as a binding-agent; it was only the bitumen on the exterior face which had such a value. It might be possible to impregnate a rock, because it was made up of particles and the interstitial spaces permited the bitumen to penetrate by capillary attraction or by pressure. The bituminous rock which was mined, and which Mr. Wood had seen in France, was nothing like the natural asphalt as laid in the streets; it was composed of a mass of fine particles and the bitumen apparently has penetrated at some time in horizontal layers. In certain cases the layers were very close together and appeared as a dark-brown streak about $\frac{1}{4}$ inch to $\frac{1}{2}$ inch deep, above and below which the layer were not so close, with the grey colour of the lime quite evident. His inquiries further indicated that the impregnated rock in some cases only contained 2 per cent. of bitumen; in the majority of cases it was 5 per cent. to 6 per cent.; in rare and isolated cases (and in comparatively small quantities) did it contain 8 per cent. or more. Yet the natural rock asphalt found laid in the streets contained not less than 10 per cent. and more nearly 12 per cent. of bitumen! How did the natural asphalt containing only 2 per cent. to 5 per cent. or 6 per cent. eventually when laid contain the higher percentages mentioned? It was obvious that, either rock containing a very high percentage of bitumen, or such bitumen as Trinidad pure, or pure bitumen from some other source, was added. What happened was illustrated by an everyday Mr. Wood.

Mr. Wood. example. When a mixture of sand and cement was to be made into mortar, it was placed in a heap and a hollow was made in the centre into which a quantity of water was poured; if left to itself for a short time the water apparently disappeared—it flowed through the air-spaces between the particles to its own level, and attained a higher level in the mass by capillary attraction, but the higher parts of the heap remained dry. As soon as a shovel was applied to the mass, and it was turned over a few times, every particle acquired by surface tension its required quantity—the whole of the water was held and evenly distributed by the individual particles. It was exactly the same with rock impregnated with bitumen. The rock was taken to a mill and thoroughly ground and disintegrated, heat was applied, and all the particles became separated, and those that had only a small percentage took up by surface tension, after mixing, the required quantity of bitumen, whether it was from heavily impregnated rock or from imported bitumen, until the whole mass was so even in composition that an analysis of any portion would give the proportion that was sought for. If a quantity of compressed asphalt from a street, showing by analysis 78 per cent. of 200-mesh material were taken as a standard, and then an equal volume of 200-mesh cement was treated with bitumen to the extent that it gave a "medium" pat paper impression (the usual test in artificial mixtures), it would be found (as he had found) that it required just about twice the quantity of bitumen that there was in the compressed asphalt. One was forced to conclude that it was therefore a fair assumption that the bitumen was held in both cases through surface tension, and that although cubes were taken as a means of measuring the surfaces they were only used because the results were similar to those that would be given if the actual superficial faces of the particles had been used. Taking the example of natural asphalt, which showed that only half the bitumen was required to secure good results, he maintained that it might be possible, when full scientific knowledge of the effects of surface tension had been obtained, to employ less bitumen, and yet secure equally good results. It was admitted that with the materials used in these mixtures and present methods of mixing, the bitumen should not be reduced; and with reference to the use of *any* material he had not intended to include materials of organic origin —though desiccated wood-fibre had been used with success. Mr. Boulnois would perhaps gather from the foregoing how there might easily be unsuccessful natural asphalts. Mr. Chapman rightly mentioned the omission of lateral support to both the base coat and wearing surface coat; lateral support by means of a curb of

Mr. Wood. concrete or granite was very desirable. In reply to Mr. Hooley, 6 inches of concrete under wood-paving had withstood for many years a very large number of motor- and steam-lorries and buses—more than were to be found on main roads in the country—with no detrimental effect; and in regard to Mr. Hooley's second question, that gentleman would be hard-pressed to find a foundation that would be satisfactory for the conditions he laid down. In Fulham several miles of the full thickness of 4 inches had been laid for 4*s*. 6*d*. per square yard, and Mr. Hooley would find it had been done elsewhere for the same (pre-war) figure. Mr. Leitch's suggestion that the cause of failure in the one-coat surfacing was not due to expansion and contraction, but to deterioration of the bitumen, was worth consideration; but where bitumen had been employed in a mixture of fine particles it had not noticeably deteriorated after 10 or 15 years, whereas the failure in the case under notice occurred in 4 to 5 years. The theory that the bitumen was subjected to much more severe conditions when large stone was used in the mixture, which prevented equal expansion in the mass, still appeared to Mr. Wood to be a more feasible cause of the defects.

Mr. Bower. Mr. Bowyer Bower, in reply, remarked that he thought the Discussion and Correspondence on the Papers would materially help the solution of the difficulties met with in road construction under present-day traffic-conditions. In all probability traffic would increase very substantially on main highways, so that increase in road-widths would have to be considered and new main highways to be constructed.

His Paper had been written more with reference to country roads than to large town roads, his observations having been made in countries where waterbound macadam roads were mostly in use, and on road construction in France during the war. The prime factor of road construction was the foundation. For this concrete, in his opinion, stood first; a very good second to it was hard soling stone scientifically packed so as to form a perfectly solid base that would not move on receiving the load above. Any movement of the foundation might cause moisture to enter the crevices, when the foundation would sink by the mud filling the crevices, and holes or corrugations would appear on the surface of the road. Under these circumstances—the result of bad workmanship—mud would probably, as Mr. Chapman said, then come to the surface from below. A hard soling scientifically packed and hard soling packed anyhow were two different things As Sir G. Scott-Moncrieff had pointed out, roads failed to be capable of standing excessive

Mr. Bower. weather and traffic conditions if they were not constructed for those conditions.

He agreed with Mr. Hooley's suggestion as to packing the soling at an angle of 45° to the traffic, but as soling stone was of every conceivable shape and size, an expert at the work would be required, and it was a question whether he could keep a uniform angle of 45° at the same speed as a man packing longitudinally. With regard to Mr. Hooley's attitude towards those who were striving to improve roads on scientific lines, traffic since the war had surpassed expectations and in all probability it would increase as mechanical engineers made further improvements in mechanical transport. The road-engineer must keep pace with requirements; so that if Mr. Hooley's 18-foot road was a main highway with increasing traffic, it would have to be widened and probably concreted as well. The day was not far distant when engineers would see the great value of concrete in road construction on roads with constant mechanical transport. As Mr. Meade-King remarked, it would be a happy day when all main roads were 60 feet wide. The cost of maintenance of a wide road would be much less per square yard than that of a narrow road, as the traffic would be more evenly distributed.

During the period of his observations the cause of waving and corrugation had been faulty foundations. Given a good solid foundation, he agreed with Colonel Crompton and others that the stone of the sub-crust ought never to be larger than 1½ inch, with as little tar mixture as would suffice to cause it to bind, thus avoiding an excessive cushion of tar-mixture between the stones, which, during hot weather, would become soft, and allow a movement in the sub-crust when traffic passed over. The construction of roads in accordance with these conditions would very considerably reduce waving and corrugation, if it did not eliminate them. In the laying of the sub-crust, if some better means of distributing it than by a fork and rake were devised, he felt sure that much of the primary waving and corrugating caused by the roller would be obviated. Even distribution of tar-macadam was very difficult; only an expert navvy could properly lay dry macadam. When a forkful of sticky tar-macadam was cast down in a mass, the centre of the mass, from the force of the fall, became more consolidated than the edges. Such masses were generally cast side by side and then raked over to the required thickness: the result was that the edges of each mass never became as solid as the centre of it, and never received the same consolidating pressure from the roller: hence depressions, which had to be filled by the carpet layer above.

This, again, caused the carpet layer to be of varying thicknesses in patches and resulted in waves and corrugations at the final rolling. He considered that every care should be taken in laying the sub-crust and carpet layer with as uniform thickness and texture as possible. If some mechanical process could be devised to attain this he thought waving and corrugating would disappear, especially if each layer were rammed or punned instead of being rolled. His experience in France showed that rammed or punned sections always had a more even surface and stood the traffic best. Hand ramming on a large scale would be out of the question, of course, but he saw no reason why mechanical ramming should not be possible. Mr. Bower.

17 December, 1918.

Sir JOHN A. F. ASPINALL, M.Eng., President, in the Chair.

The discussion upon the Papers by Messrs. Leeming, Wood and Bower on Road Construction and Maintenance occupied the evening.