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Factors Affecting the Dynamic Behaviour of Higher Speed Agricultural Vehicles

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The gradual transition towards higher working speeds in agriculture and greater use of specialized transport-oriented vehicles poses technical problems. These are related to the general deterioration in dynamic behaviour associated with increased speed and can be categorized into the following areas: (a) ride vibration; (b) steering and handling and (c) control of implements.

Results from mathematical models are shown to highlight some interesting features of the suspension, steering and linkage design of off-road vehicles. Further use and refinement of these models will depend on the commercial pressures to replace conventional agricultural equipment with higher speed alternatives.

1. Introduction

The debate about transport requirements in agriculture and the role of the conventional tractor has attracted much interest recently. Göhlich,[1] in his review paper, drew attention to the growing requirement for more efficient transport and the pressure towards operating tractors at higher speeds. Despite the fact that tractors would remain the key machine for agricultural production in the near future, he iterated the widely held views of what the future held for agricultural vehicles, namely:

(a) more-specialized vehicles;
(b) more-comfortable vehicles;
(c) more information displayed;
(d) less use of tractive power but greater use of p.t.o. power and
(e) lower ground pressures, less compaction.

The tractor has already been displaced from some of its previous tasks by self-propelled machines, either totally (as for combine harvesting) or partially (as for forage harvesting, spreading, spraying and materials handling). There are powerful arguments why the next task on this list will be transport. The conventional tractor is designed essentially around the high-draught, low-speed operation. Despite this, it is used for virtually every other agricultural task that requires a mobile power source, and its efficiency at performing these tasks is severely compromised by the high-draught requirement. Studies of tractor usage patterns are notoriously difficult to assess because of the wide differences in farms, but one feature that they continually highlight is the large percentage of time spent on transport and related tasks—typically 40–50%. If light p.t.o. duties are added to this figure, then the total can reach 60–80%. One interpretation of the foregoing comments is that the agricultural vehicle should be designed primarily around performing transport, and perhaps light p.t.o., tasks efficiently. This implies a divergence of two main vehicle types; one designed to optimize transport and one designed to optimize draught operations. The latter is likely to be a four-wheel drive or tracklaying tractor.

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Fig. 1. Trantor—a high-speed tractor

Fig. 2. NIAE experimental farm transport vehicle

Whatever form the transport-oriented vehicle takes, one thing is clear. It will operate at significantly higher speeds than conventional tractors. This paper is concerned solely with the effect of speed on off-road vehicle design. Since there are three problems relating to speed, the paper is divided into sections dealing with each one: (a) ride vibration; (b) steering and handling and (c) control of implements.

Two different concepts of high-speed agricultural vehicles are shown in *Figs 1* and *2*. The first is called "Trantor". It has suspended axles, a novel suspended hitch and is capable of road speeds up to 80 km/h. The second is called an "Experimental Farm Transport Vehicle" (EFTV) and was developed at NIAE, Silsoe. It has been designed as a vehicle which can be used experimentally to assess the feasibility of higher speed agricultural operations. A range of demountable bodies has been developed to enable the vehicle to perform a range of operations. It steers by articulation between the front and rear chassis, has actively controlled suspension and is capable of 65 km/h.

The work described in this paper forms part of two research projects at Leeds University in collaboration with the design teams of these two vehicles.

2. Ride vibration

The effect of speed on ride vibration levels was studied theoretically using simple models of off-road vehicles. For the unsuspended versions of these vehicles, the model had three degrees of freedom—bounce, pitch and longitudinal motions. For the suspended versions, two extra degrees of freedom, describing the front and rear axle motions were introduced. The main dimensions and co-ordinates of the model are shown in *Fig. 3*.

The main assumptions relating to these models are as follows.

(a) The vehicle is treated as a rigid body in two dimensions only, i.e. in side elevation, so that roll and lateral motions are neglected.

(b) The tyre is modelled as a linear spring and damper in both the vertical and longitudinal directions.

(c) The ground profile characteristic can be described by the well-known equation

$$S_x(\Omega) = G\Omega^{-P},$$

where $S_x(\Omega)$ is the displacement spectral density (in m^2 $(\text{cycle/m})^{-1}$), Ω is the wavenumber (in cycles/m), G is the ground roughness coefficient and P is an exponent.

(d) The tyre envelops the surface over which it travels in such a way as to filter out the higher frequencies, i.e. the tyre frequency response function is unity up to a wavenumber around its contact length and it decreases above this wave number.

Briefly, the justification for using such a simple model is as follows. First, we are primarily interested in the effects of substantial design changes, e.g. revised vehicle layout, addition of an implement, etc. Second, the aim of the modelling is not to predict absolute vibration levels with accuracy, but rather to produce design guidelines by aiding understanding of the relative effects of design changes. Other authors[2] have recently pointed out that more complicated tractor models are incapable of predicting frequency and amplitude information accurately, due essentially to a lack of a detailed understanding of the tyre behaviour.

The mathematical techniques for ride analysis are well-established, and applications to off-road vehicles have been described by various authors.[3-6] In the work described here, an idealized spectral density of the ground input was combined with the frequency response functions of the vehicle and its tyres to obtain output power spectral densities. Further details can be found, if necessary, in the paper by Horton and Crolla.[7] Three outputs are likely to be of interest to a designer: displacements of the suspension, accelerations at the driver's seat and tyre–ground contact forces.

To investigate the effect of speed, power spectral density (p.s.d.) curves of these parameters for a range of speeds were calculated. Clearly, this results in an overwhelming amoung of information, so the p.s.d. curves were further processed to obtain the r.m.s. values, i.e. a single figure obtained by integrating the p.s.d. curve over the range 0·1–10 Hz. An example of plotting r.m.s. acceleration level at the driver's seat against forward speed is shown in *Fig. 3*.

Three sets of vehicle data were used to compare the effect of various vehicle layouts. They were not intended to represent specific vehicles, but rather to be typical of the geometry of different vehicles.

The data are shown in Table 1, the relevant dimensions being defined in *Fig. 4*. The first column refers to a conventional tractor and if the hypothetical suspension data are used then a vehicle

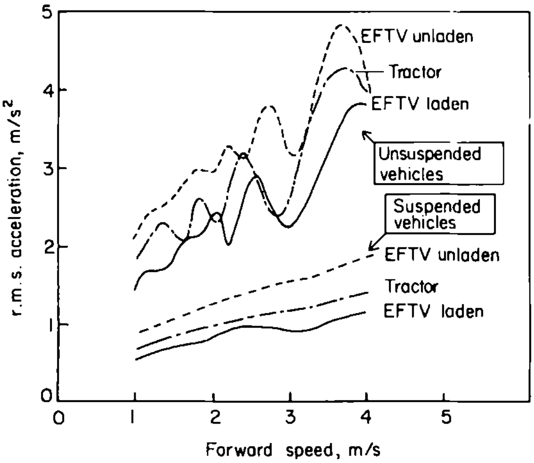

Fig. 3. Predicted r.m.s. vertical acceleration at driver's seat for the vehicles on an off-road surface

TABLE 1

Data for vehicles used in ride vibration predictions

	Tractor	*EFTV unladen*	*EFTV laden*
Body mass, kg	4000	4000	5000
Body pitch inertia, kg m^2	5000	8000	18,000
Front axle mass, kg	250	500	500
Rear axle mass, kg	750	500	500
Wheelbase, m	2·4	3·6	3·6
Distances (see *Fig. 4*)			
x_f, m	1·0	1·6	1·9
x_r, m	1·4	2·0	1·7
x_s, m	0·6	1·4	1·7
z_s, m	0·5	0·5	−0·1
z_g, m	0·9	0·9	1·5
Tyre properties (per axle)			
k_x, kN/m	900	900	900
k_z, kN/m	900	900	900
c_x, kN s/m	5·0	5·0	5·0
c_z, kN s/m	5·0	5·0	5·0
Suspension properties (per axle)			
k_s, kN/m	400	400	400
c_s, kN s/m	20	20	20

similar to the Trantor is simulated. The second and third columns refer to a vehicle with a layout similar to that of the EFTV. Both the unladen and laden cases are included.

The results of the unsuspended versions of the vehicles (*Fig. 3*) are particularly interesting, because they show that the relationship between r.m.s. acceleration and speed is not as simple as might first be imagined. The characteristic waviness of these results is caused by the interaction between the vehicle frequency response and the so-called "wheelbase filtering" effect. The vehicle frequency response is a characteristic of the vehicle dynamic behaviour and is independent of speed. The wheelbase filtering effect is a characteristic of the input disturbance to the vehicle from the road and it depends on vehicle speed.

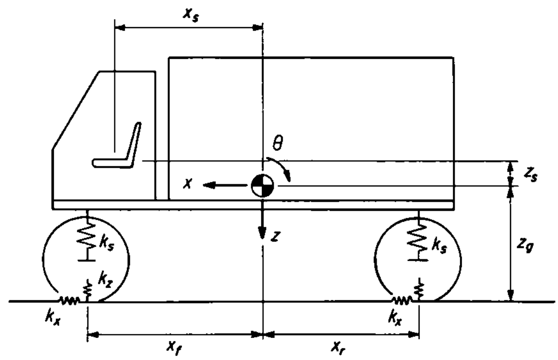

Fig. 4. General vehicle ride model showing dimensions and co-ordinates

The wheelbase filtering effect, though commonly referred to in the literature, requires some further explanation. The inputs at the front and rear wheels are related by the fact that the rear wheel follows the same profile as the front wheel but the rear input is delayed by a time of l/v seconds relative to the front input, where l is the wheelbase and v is the forward speed. If the ground displacement spectrum is thought of as a set of discrete sinusoidal components, the wheelbase effect results in some components which emphasise bounce motion. A component in the ground spectrum of wavelength l/n metres ($n = 1, 2, \ldots$) will provide in-phase inputs at front and rear wheels, tending to excite bounce motion and suppress pitch motion. Conversely, components with wavelength $l/(n-\frac{1}{2})$ metres result in out-of-phase inputs which have the opposite effect.

In practical terms, these results are of great significance since they emphasize that the effect of vehicle speed on ride vibration is not a simple one. For example, for the laden EFTV they indicate that if the vehicle speed is increased over a given surface from 2·5 to 3 m/s a decrease in r.m.s. acceleration level would be obtained, whereas increasing speed further, from 3 to 4 m/s would result in a dramatic increase. Equally, if all three vehicles are compared at speeds of, say, 2·8 and 3·5 m/s, quite different results would be obtained. In practical measurements, r.m.s. acceleration levels do not appear to be as sensitive to speed as is indicated by these theoretical results. This is because of the difficulties of maintaining a constant forward speed. Variations around a mean speed are usually significant and cause a smoothing of the curves shown.

With the suspended versions of these vehicles, not only are the overall r.m.s. levels reduced considerably, but they are less sensitive to the wheelbase effect, as indicated by the smoother curves. This arises because the frequency response curves of the suspended vehicles are smoother overall and do not contain such pronounced peaks as their unsuspended counterparts.

The predicted results of r.m.s. acceleration levels for running the suspended versions of the vehicles on a smoother surface at much higher speeds are shown in *Fig. 5*. The results for the off-road surface are also shown for comparison. They highlight two features. First, the relationship between r.m.s. acceleration levels and speed is still not a simple one for the suspended vehicles at higher speeds. For example, comparison of the unladen farm transport vehicle and tractor at speeds of 10 and 12 m/s would give apparently conflicting results. Second, the suspended vehicle is less sensitive to speed than the unsuspended vehicle. This is shown by the average slopes of the curves, which are lower for the suspended vehicle either on or off the road than for the unsuspended vehicle.

The information relevant to suspension design is shown in *Fig. 6* for the laden farm transport vehicle running on an off-road surface. R.m.s. values of vertical acceleration at the driver's seat, front suspension displacement and front wheel load are plotted against speed for two suspensions. The compromise between improving comfort at the expense of increased suspension travel and wheel-load variations is quantified. The softer suspension has parameter values which give excessive values of suspension deflection between unladen and laden conditions and would,

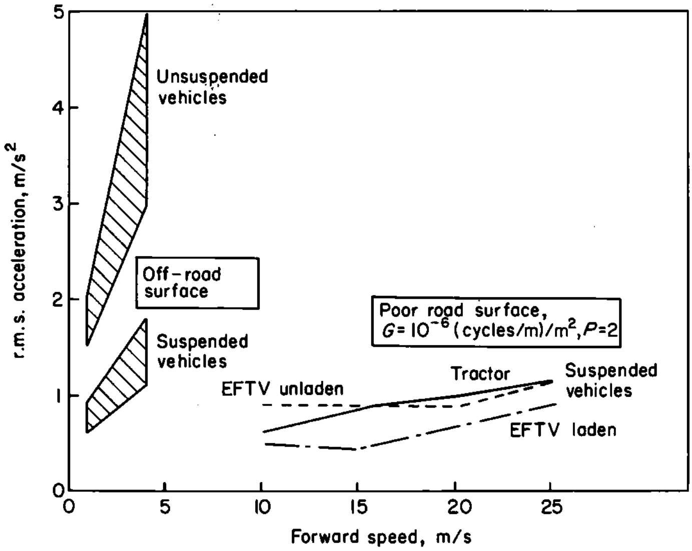

Fig. 5. Predicted r.m.s. vertical acceleration at driver's seat for the vehicles at higher speeds on a poor road surface

therefore, require some form of self-levelling feature. Although various designs of self-levelling suspension are already produced for commercial vehicles, their considerable benefits can only be gained at the expense of additional original cost of the suspension.

3. Steering and handling

When designing off-road vehicles to operate at higher speeds on reasonably good surfaces, e.g. tracks or poor roads, much of the conventional wisdom relating to road vehicles applies. This is particularly true if the vehicle itself is steered conventionally. However, there are two particular stability problems which can arise. The first potential problem is with articulated frame steer vehicles and the second is with a combination of a conventionally steered tractor and a large unbalanced trailer. The NIAE experimental farm transport vehicle falls into the first category, and the Trantor falls into the second category since it is commonly used with trailers weighing several times its own weight.

Again, simple mathematical models were used to predict the effect of speed on the stability on the two vehicles mentioned. The details of these models are given elsewhere[8,9] and will not be repeated here. Briefly, the main assumptions are as follows.

(a) The vehicle bodies have freedom to move in the forward, lateral and yaw directions.

(b) The bodies are kinematically constrained relative to each other by the trailer hitch or frame steer pivot, both of which allow freedom in the yaw direction. For the frame steer pivot, it is assumed to be constrained by a torsional spring and damper which simulate the hydraulic steering components.

(c) The tyre lateral force is related to slip angle by an exponential equation, which may be linearized for small slip angles.

(d) To investigate stability under constant speed running conditions, the set of equations is linearized and solved to obtain eigenvalues and eigenvectors. The assumption of constant forward speed removes the longitudinal degree of freedom in this case.

(e) For other manoeuvres, which may involve braking, steering, accelerating, etc., the equations are solved as a time history simulation.

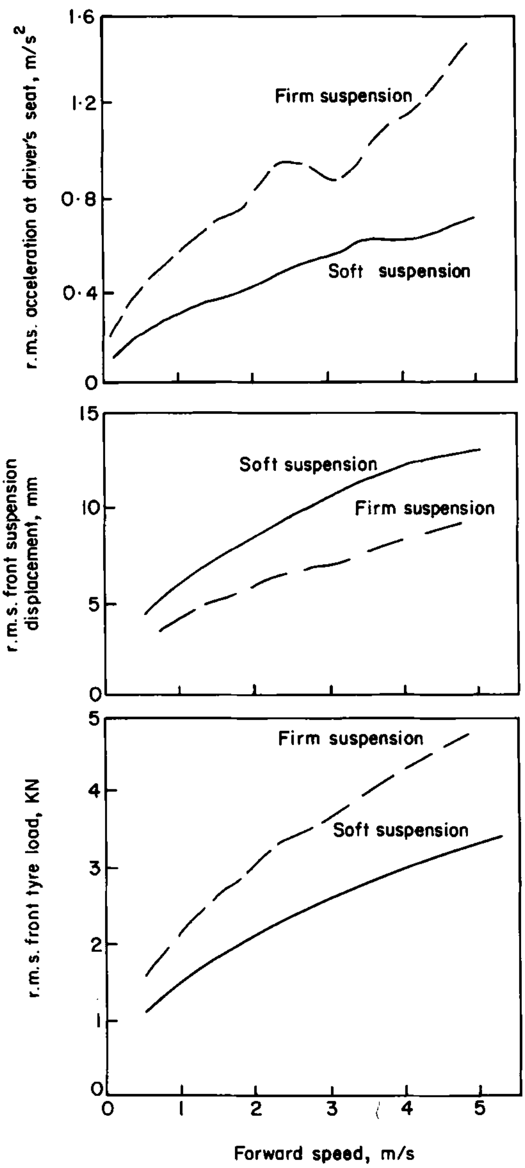

Fig. 6. Predicted r.m.s. values of vertical acceleration, suspension movement and tyre load against forward speed for the laden farm transport vehicle with two different suspensions

The justification for using these relatively simple models is based on experience established for road vehicles. Providing reasonably accurate tyre data are available, which is true for the smaller range of off-road tyres,[10] then these models contain all the key features of the problem. As such, one may expect to use them with some confidence to investigate substantial design changes and give some insight into their likely effect.

Typical results summarizing the effect of speed on the stability of articulated frame steer vehicles are shown in *Fig. 7.* The two sets of data used are typical of a farm transport vehicle layout and a large, four-wheel drive tractor layout. The parameter plotted, real part of the eigenvalue, provides a direct indication of stability. A large negative value indicates a well-damped system, whereas a

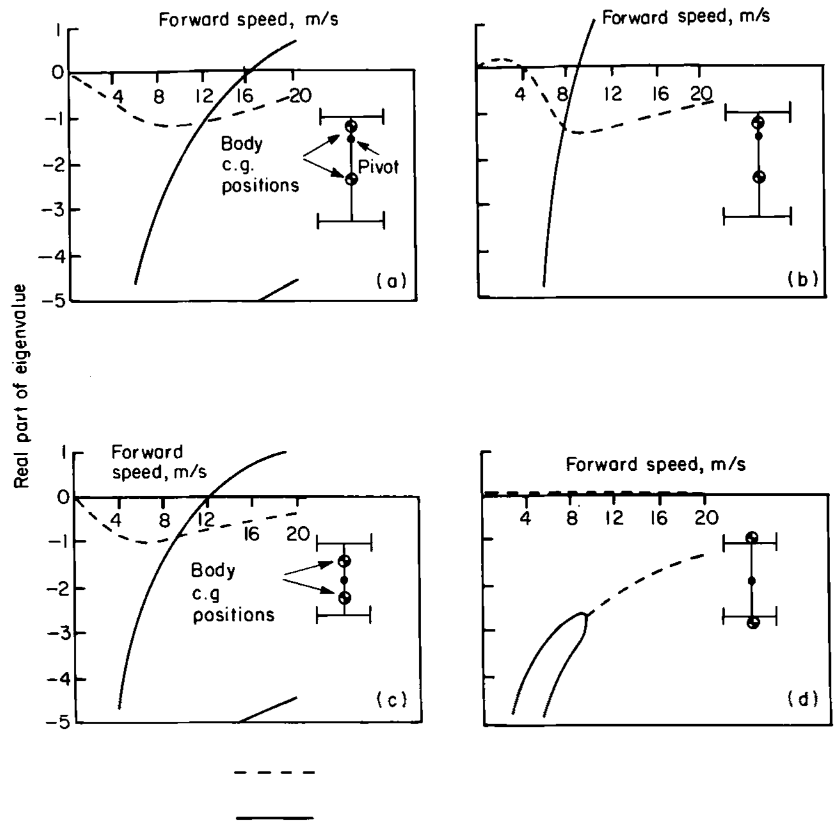

Fig. 7. Predictions of the relative deterioration in handling stability of articulated frame steer vehicles with forward speed. (a) Unladen EFTV, (b) laden EFTV, (c) articulated agricultural tractor, (d) articulated agricultural tractor with altered c.g. position. ----, oscillatory root, ———, exponential root

positive number indicates an unstable system. The instability may be an oscillatory type as shown by a broken line, or an exponential type as shown by a solid line.

The first feature that these results show is the general reduction in damping levels as speed increases. This is expected as it occurs equally with road vehicles. The second feature is that two types of instability can occur. These are:

(a) a collapse mode (solid line), in which the two body portions fold together rather like the "jack-knife" behaviour of an articulated lorry and

(b) a weave mode (broken line), in which the two body portions oscillate in the yaw direction, out of phase with each other.

The limited experimental evidence available to date agrees both qualitatively and quantitatively with this predicted behaviour.

Two examples of the effect of design features are highlighted in *Fig.* 7. The effect of a full load on the farm transport vehicle is to reduce the critical speed from 17 m/s for the unladen vehicle to around 8 m/s. On the large agricultural tractor with a similar steering arrangement the effect of moving the c.g. positions outside the wheelbase is to avoid the collapse instability, but at the expense of a weave instability throughout the entire speed range. In practice, this may be typical of such a tractor transporting a heavy mounted implement at the front or rear.

The tractor and trailer combination has been shown to exhibit two analogous instabilities which are descriptively referred to as a jack-knife (oversteer) and a trailer swing instability.[9] Increasing

TABLE 2

Critical speeds at which instability occurs for a typical 60 kW tractor and 8 t trailer

		Critical speed at which instability occurs m/s
Surface type	Slippery, $\mu = 0{\cdot}3$	13
	Dry grassland, $\mu = 0{\cdot}6$	18
	Tarmac, $\mu = 1{\cdot}0$	Stable
Change in load distribution from baseline condition	Tractor c.g. moved 0·5 m aft	8·5
	Trailer c.g. moved 1 m forward	8·0
Change in tractor hitch position	0·3 m forward of rear axle	Stable
	1 m aft of rear axle	9·5

speed tends, eventually, to result in one of these instabilities, and the effect of various parameter changes on the critical speed at which instability occurs is summarized in Table 2. The data refer to a conventionally steered 60 kW tractor towing an 8 t trailer. The results show that fairly minor changes in loading or hitch position can transform the combination into one which is becoming dangerous at its current top speed of 8–9 m/s. Clearly, in designing a higher speed combination it would be inappropriate simply to uprate the existing layout. The model does, however, point to some key design features, for example, hitch position in the results quoted, which improve vehicle stability at higher speeds.

4. Control of implements

There are two separate types of implement, each of which poses different problems in its control; those which are soil-engaging and those which operate above the ground surface. The soil-engaging type, e.g. plough or cultivator, requires some form or depth or draught control whereas the other type, e.g. sprayer or spreader requires control of its height above the ground.

For the soil-engaging implements, the deterioration in conventional draught control performance with increasing forward speed has been thoroughly discussed.[11,12] Basically, the hydraulic control system has a limited frequency response, so the performance deteriorates at the higher frequencies arising from higher speed operation. There are methods of improving the control system, although they all require additional cost. For example, increasing rates of linkage movement, decreasing deadband and decreasing delay time are all possible for a control system which senses pure draught force. They are not possible with current top or lower link sensing designs because they cause instability of the control.

However, soil-engaging implements, in particular ploughs, have another effect on tractor performance. Because of the damping effect arising from vertical soil forces, the implement is beneficial in reducing tractor ride vibration levels. The improvement can be as much as a 50% reduction in tractor r.m.s. vertical acceleration at the driver's seat.[13]

Unfortunately, the improvement is in conflict with the requirements for accurate draught control. The damping forces are transmitted to the tractor through the three-point linkage. However, the draught control system senses this linkage force, in either top or lower links, and since some of the changes in this force are not due to variations in implement draught, spurious control signals are received. This problem can be overcome with a pure draught sensing system[14] which senses both top and lower link forces and sums them, because the spurious fluctuations arising from vertical force variations then cancel out.

There are, therefore, design difficulties if higher-speed operation is going to apply to cultivation as well as other operations. The ideal would be to capitalize on the improved ride level but to retain adequate control of the implement. Unfortunately, although mathematical models are available

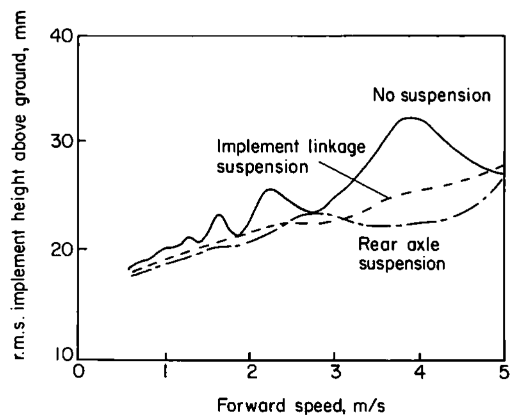

Fig. 8. Predicted r.m.s. values of implement height above the ground against forward speed for three vehicle suspension types

which treat the two issues separately, nobody has yet devised a simple model which incorporates their interaction. Furthermore, the problem is complicated by the possible addition of axle suspension to the tractor. This, however, also leads on to a consideration of the implements above the ground.

With an implement such as a spreader which is rigidly attached to a tractor or other vehicle, the r.m.s. implement displacement value increases with speed in a manner similar to that already depicted for driver's seat acceleration. The actual value depends on the geometry of implement relative to the vehicle and in the cut-off value of wave number, Ω, associated with the definition of the ground spectrum, $S_x(\Omega)$. A value of 0·1–0·2 cycles/m is typical. The calculation of implement acceleration or displacement is rather simple, because if it is rigidly attached, then the model already described may be used with the input modified appropriately. Increased speed, therefore, results not only in reduced operator comfort but also deterioration in quality of work in cases where implement height above the ground is important.

Further treatment of this problem is amenable to analysis using the simple ride models already described, but with slight modification. It leads to two concepts for reducing the implement height variations; an unsuspended vehicle with implement suspension or a suspended vehicle with rigidly attached implement. The first of these clearly implies an extra degree of freedom in the model to describe implement motion relative to the vehicle. Predicted results of r.m.s. implement vertical displacement for these two layouts are shown in *Fig. 8.* The suspended vehicle has suspension on the rear axle only. This arrangement was simulated in order to investigate whether suspending one of the axles was a reasonable design compromise between full and no axle suspension. The data used, shown in Table 3, refer to a typical self-propelled vehicle with an implement such as a sprayer boom. The parameter values selected for the suspension stiffness and damping are intended to be a good practical compromise. They have not been formally optimized so there may be scope for further slight improvement. Both proposed layouts show a marked improvement over the base vehicle with no suspended elements, and the axle suspension is better on average than the linkage suspension.

The method of attaching the three-point linkage to a higher speed off-road vehicle depends largely on whether it will be used with soil-engaging or non-soil-engaging implements, or both these types. For the non-soil-engaging implements, the considerations of the suspension design are reasonably straightforward and are dominated by the usual compromise between suspension travel and improvement in ride behaviour. For the soil-engaging implements, the performance of the draught control unit must also be considered. However, the problem of how the control system interacts with the ride behaviour of the combination is still unresolved. An additional consideration is the point on the vehicle at which the draught force is reacted. This suggests connecting the linkage

TABLE 3

Typical data for four-wheel drive self-propelled vehicle with rear-mounted implement used in implement height predictions

Body mass, kg	7500
Body pitch inertia, kg m^2	25,000
Rear axle mass, kg	750
Implement mass, kg	600
Wheelbase, m	3·2
Distances (see *Fig. 4*)	
x_f, m	1·1
x_r, m	2·1
x_g, m	1·3
Body c.g. to implement, c.g., m	4·0
Tyre properties (per axle)	
k_z, kN/m	800
c_z, kN s/m	8·0
Suspension properties	
rear axle stiffness, kN/m	400
rear axle damping, kN s/m	25·0
implement stiffness, kN/m	25
implement damping, kN s/m	2·5

directly to the rear axle, and this has been done in two of the designs which are commercially available. On the Trantor, the three-point linkage is connected to the rear axle assembly and suspended relative to this assembly. On the Unimog, the lower links are connected to the rear axle, whilst the upper link is connected to the vehicle body. Thus, small changes in linkage geometry can occur with deflection of the axle suspension. Both these systems have some position control of the linkage, but neither has a draught control.

Finally, there is a potential advantage to be gained from suspending the pick-up hitch when the vehicle is used with unbalanced trailers. The dynamic coupling of a tractor and trailer combination has been studied both theoretically[15] and experimentally,[16] and a suspended hitch was predicted as improving ride comfort by virtue of the damping which could be introduced. These results only applied to conventional unsprung agricultural tractors and trailers. Unfortunately, there are considerable practical difficulties in designing such a hitch because of space limitations.

5. Conclusions

The main conclusion is that simple models of the dynamic behaviour of higher speed agricultural vehicles are useful in producing design guidelines. Such models, however, cannot predict dynamic behaviour precisely and are, therefore, only valid when comparing substantial changes in design parameters.

The technical problems associated with higher operating speeds have been categorized as: (a) ride vibration; (b) steering and handling and (c) control of implements. Some general conclusions about each of these topics are outlined below. However, for design information on specific vehicles, it is recommended that the simple models referred to in the paper are used with the appropriate data for the particular vehicle.

The effect of speed on vehicle ride vibration is not straightforward. Comparisons should be made over the operating speed range of the vehicle, because the conclusions drawn for one operating speed may be misleading. Higher speed agricultural vehicles will inevitably incorporate axle suspension, and using simple models, the design compromise between ride comfort, suspension travel and dynamic wheel loads can be quantified.

For steering and handling behaviour, the main dynamic problems are likely to arise with multibody vehicles, e.g. articulated frame steer tractors and tractor–trailer combinations. Simple models can not only predict the critical speed at which oversteer or weave instabilities occur, but also indicate remedial design changes. For example, stiffening the torsional compliance at the pivot of an articulated frame steer vehicle or moving the tractor hitch forward in a tractor–trailer combination both improve stability.

When implements are attached to the vehicles, it is often necessary to control either height above the ground or depth below the ground surface, depending on the type of implement. For implements requiring height control, a suspended linkage can be beneficial if the vehicle does not have axle suspension. For implements requiring depth control, there are mathematical models available which describe the hydraulic control system and enable the deterioration in performance with increasing speed to be quantified. However, the important step of combining the vehicle ride and implement control models awaits attention.

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