OPERATIONAL AND TECHNICAL REQUIREMENTS INFLUENCING THE SHAPE OF AGRICULTURAL TRACTORS

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Per Ebbe Sverker Persson

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This is to certify that the

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by

Sverker Per Ebbe Persson

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies of
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ABSTRACT

All implements for farming operations need power in some form. For field operations this power is now generally supplied by an automotive power unit consisting of engine, transmission, wheels and means for control and for attaching implements, all mounted in a suitable frame. It seems likely that an automotive power unit containing the same basic parts and interchangeable between different implements, will be used for field operations in the future also. For farmstead operations other types of power units seem preferable.

The implements and the power unit are now both mechanical devices which could be integrated into one operational unit. In order to increase the operational efficiency this integration should be carried as far as possible. When judging existing designs and developing improved designs implement and power unit should therefore be treated together as one unit.

The implements are the most important parts of the combination implement -- power unit, because they perform the direct operation on the soil, the product, etc. The requirements of the implements should therefore be given the primary consideration. Some of these requirements are operational, being dictated by the product and the method for handling the product; others might be called technical, being connected to a certain design of the implement. The operational requirements refer to such factors as supervision, height control, steering and

other adjustments, position within operational unit, field conditions, quantities of product involved, etc. Requirements from the implements on horizontal pull, vertical and lateral supporting forces, power for rotating parts, speed and speed adjustment, room needed for implement, etc., may be classified as technical requirements.

Also the functional requirements of the elements of the power unit must be satisfied if an efficient combination implement -- power unit shall result. Because this study is limited to requirements affecting the general shape of the power unit, the only thoroughly discussed requirements from the power unit are the requirements on good drive and steering effectiveness, sufficient stability and suitable driver position. Some tractor mechanics needed for the discussion of these requirements are given in Appendices A and B.

Many implements are now combinations of elements performing different functions. In this study such implements have been broken apart in their elements and the requirements referred to the elements instead of to the whole implement. In this way it is possible to arrange each element in its best position and to determine the effectiveness of other arrangements and other combinations than are presently used.

The operational and technical requirements of the implements are briefly listed in tables 201-215 and the functional requirements of the parts of the power unit discussed in section III. Especially the tables 210-215 are incomplete because the information needed is not available.

Starting from the requirements power units can be developed. The procedure suggested in section IV is to start making power units for a single implement. In this way the requirements of that implement can be satisfied as far as possible. The most efficient operational unit should be found in this way. Factors to be determined at this stage are wheel, drive and steering arrangement, weight distribution and engine power.

There are, however, only very few cases where a power unit for economical reasons can be used for only one implement. In some cases the individual power units for different implements might be similar enough to permit the use of the same power unit for these implements without any important change, but in most cases compromises in the design must be made. Most consideration must thereby be given to the requirements of the most important implements. The importance of an implement may be measured by the area for which it is used, by the number of times it is used, by the value of the product processed, etc.

It is probably not possible to make a single, general purpose power unit for all types of implements without a great loss of effectiveness for at least some of the implements. Differentiated power unit types, for instance tillage tractors, harvest tractors, etc., will, however, presumably be needed as the demand for more efficient power increases.

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Sverker Persson

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INTRODUCTION

The aim of man always has been to employ power as extensively as possible to his services, thereby making it possible for him to produce more and secure a more comfortable living, the word comfortable taken in a broad sense. This has been true in agriculture, too. The earlier steps have been the replacement of human energy by animal energy. Today, this evolution means using larger and larger mechanical power units (electric, atomic, solar included). We are, however, in agriculture far from using the largest power units available in other fields.

The limit for the size of the power unit usually is set by economic factors, but sometimes technical difficulties--both on the power-unit side and on the implement side--make the application of large power useless. The economic limit is determined by the size and type of farm, the labor situation, et al.; and it changes from time to time. The technical limit can be pushed further away through new methods of converting the power in efficient work, through combination of operations, through developing entirely new methods for a certain basic operation, and so forth. This study will be limited to the efficiency in converting power into desired work of the kind normally used today and will leave open the possibilities of using entirely new methods of treating the soil, the crop, etc. The economic limit cannot be discussed at any length, but will be mentioned briefly.

Connected to and of the same importance as the tendency of using bigger sources of power for a certain operation is the tendency of reducing the human effort needed for the same operation. Though far from completed, great progress has been made in the efforts to reduce human physical work. The psychical strain (inconvenience) has not been reduced to the same extent and actually has been more accentuated in some cases. This study will, as far as possible, take these aspects in consideration, too.

The two tendencies mentioned always have existed more or less pronouncedly. The reason why a study of the basic design of the power units seems justified just now is that the possibilities of further improvements of existing power units by only slight changes in their design seem limited. Many power units still operate on the same principle as their predecessor the horse, i.e., by merely pulling the implement. A mechanical power unit can be capable of doing much more than this; these additional possibilities could be advantageously utilized for many operations. The possibility of mounting the implement directly on the tractor has been used to some extent and has meant a great improvement in some cases. The general shape of the tractor, however, usually has not been changed in such a way that we can take full advantage of the possibilities of mounting implements. The number of implements that can be mounted is limited.

There is an increasing tendency to use self-propelled implements for certain operations. In this case, the power unit is used for only one implement and can therefore be tailor-made for its requirements. In this way, an operational unit with the highest possible efficiency ought to be found. From an economic standpoint, however, it seems impossible to make all implements self-propelled. Before accepting this as the goal of the evolution, all other ways should therefore be investigated to see if it is possible to reach, or at least approach, the indisputably superior operational performance of the self-propelled implement using the same power unit for several implements.

Limitations and General Assumptions of this Study

As mentioned previously, the study will be limited to farming operations as we know them today, either that they have been used for a long time or that they have been developed lately but show such promise that they can be supposed to be in practical use in a near future. Beside this, further assumptions must be made according to the conditions on the farm for which the power unit and its implements has to be selected and where they have to work. I assume that some of the more important ones in this connection must be:

1. The only source of power for field work will be a power unit with an internal combustion engine of any type. For work in, or in the neighborhood of, the farm buildings, either electric motors or internal combustion engines would be used, with a preference for the former. No animal power will be used.
2. Normally there will not be more than one operator on each machine. The possibility of one operator handling two or more machines will be discussed in the study.
3. The farm always will consist of several fields. There usually will be more than one product produced (different animal products included) with the objective of minimizing the risks if one

product should fail. The number of products on each farm, however, will be smaller than today.

4. I will disregard, from a functional standpoint, such irrelevant reasons as styling and convention.

The study is intended to give some aspects on the future development of the power unit. Types which do not exist today therefore will be discussed together with existing construction. This extension of the field of discussion will be indicated by the use of the words "power unit" instead of the word "tractor," with the purpose not to lead the thought to the shape of the tractor of today. The expression "power unit" will include all types. e.g., those of self-propelled machines, and will be more strictly defined later on.

As mentioned above, the self-propelled implement, specially designed for a single operation, ought to be the most efficient unit for this operation. A logical first step seems, therefore, to be to study the basic operations and the implements used to perform them and to determine which requirements these implements have on their power units. The next step is to try to find the best power unit for two or more operations or implements. This usually will involve a compromise; consequently, some measure of the relative importance of the operations is needed. These factors might be called operational and are treated in Sections I and II.

Of course, there are technical factors determining the basic shape of the power unit. As such can be mentioned traction, steering, and stability of the power unit. The equations governing these factors are given in Section III.

The different tractor types are described and compared in Section IV, using the earlier discussion of the factors which ought to determine their shape.

SECTION I. FARMING OPERATIONS IN WHICH A POWER UNIT IS NEEDED

Chapter 1. A General Review of Farm Operations and their Power Sources

This study later on will discuss only the automotive agricultural power unit, i.e., a power unit with similar tasks as the present agricultural tractor. It may, however, be worthwhile to start with a more complete list of farm operations and implements and to indicate what other power sources might be used besides the mobile power unit. In some cases, depending on the conditions, alternative power sources might be used.

A first division of the operations may be made into:

1. field operations, i.e., operations dealing with the plants;
2. farmstead operations, i.e., operations dealing mainly with the animals and the processing of agricultural products.
3. transportation of farm products;
4. forestry operations (will not be treated here).

Some operations could be carried to more than one of the groups.

Field Operations

These operations include preparation of the soil before planting, planting and caring for the plant when it is growing, and harvesting.

TABLE 101. FIELD OPERATIONS AND SUITABLE POWER UNITS.

Operation	Type of power source: Best alternative	Equally good alternative	Unusual alternative
Field improvement:			
Land clearing, Drainage, Terracing, pond building	contr		apu
Land smoothing	apu	contr	
Soil preparation:			
Plowing			
Moldboard plow, Disc plow, Rotary plow	apu		
Shallow plowing	apu		
Harrowing, cultivating			
Heavy cultivator, Rotary cultivator, Light harrow	apu		
Rolling	apu		
Spreading lime	contr	apu	
manure	apu		
solid fertil.	apu		contr
liquid "	apu		contr
Planting and care of the plant:			
Planting			
Small grain and grass seed, Corn and beans, Beet seed, Potatoes, Seedlings	apu		
Thinning	apu		
Spraying	apu	contr	
Dusting	contr	apu	
(Cultivating)			
(Topping)			
Harvesting			
Grass and legumes			
Mower (cutting the crop), Tedder, Rake, Grass loader	apu		

Abbreviations, see page 11

TABLE 101, cont.

Operation	Type of power source		
	Best alternative	Equally good alternative	Unusual alternative
Hay loader	apu		
Baler	apu	contr	
Chopper	apu		
Small grain and grass seed			
Windrower }	apu		
Binder }			
Combine	apu	contr	
Corn			
Corn picker }	apu		
Corn sheller }			
Potatoes			
Potato stalk cutter }			
Non-collecting potato harvester }	apu		
Collecting or direct loading potato harvester	apu	contr	
Root crops			
Root lifter }	apu		
Topper }			
Collecting root-harvester }	apu	contr	
Pick-up root loader }			
Special crops (vegetables etc.)	apu	contr	
Preparing the harvested crop for the market (stationary or semistationary equipment)			
Dryer for grain (hay)	elmo		apu
Cleaner for grain	elmo	contr	
Grader, dryer, etc. for various crops	elmo		

Abbreviations, see page 11

Farmstead Operations

The basic operations are, to a great extent, the same for all common kinds of animals; cattle, (horses), swine, and poultry. They include preparation and distribution of the feed, cleaning of the buildings, and milking. A great part of the operations connected with the animals may be classified as loading and transportation and is placed accordingly in that group. Some other operations often are included in the daily process of feeding cattle, e.g., cutting and chopping grass or corn for feed, but these operations are in themselves field operations and as such are included in the group operations connected to the plant. Manure spreading is another such daily operation on some farms..

Loading and Transport Operations

Certain of the operations mentioned earlier include a loading or transportation part, but this is only a minor part of the whole operation carried out by the machine. Loading is, in itself, a sort of transportation and sometimes can be carried out by the same implement as performs the transport in a more restricted, common notation.

In tables 101 - 103, some possible power sources for the different implements (operations) have been given in order of importance. The "best" alternative does not always reflect what is presently most common, but what could be considered good practice under most conditions. In quite a number of cases, however, the "equal" alternative may be the best, and in a few;

TABLE 102. FARMSTEAD OPERATIONS AND SUITABLE POWER UNITS.

Operation	Type of power source: Best alternative	Equally good alternative	Unusual alternative
Feed preparation:			
Grass and legume crops			
Stationary chopper	elmo	apu	
Silo distributor } Silo unloader	elmo		
Grain			
Mills	elmo		apu
Mixers	elmo		
Feed distribution	elmo	pneum., hydr.	
Barn cleaner: conveyor type	elmo		
washing type	elmo		
Milking machine	elmo		stat
Water supply	elmo		stat
Workshop: power tools	elmo	pneum.	
welding	line	elmo	apu or stat
Emergency electric power supply	apu	stat	

Type of power source:

apu = agricultural power unit, automotive, 'farm tractor'
contr. = contractor's (seller's, buyer's) unit, tractor, vehicle
elmo = agricultural electric motor
stat = stationary engine, movable, not connected to a power supply
farm = farmer's own
hand = hand operated
pneum. } = pneumatically (hydraulically) operated
hydr. }

TABLE 103. LOADING AND TRANSPORT OPERATIONS AND SUITABLE POWER UNITS.

Operation	Type of power source: Best alternative	Equally good alternative	Unusual alternative
Loading:			
front loader and other loaders attached to the tractor and taking one piece at a time	apu		
continous loader	apu and elmo	stat	
heavy loader, excavator and crane	contr		apu
stationary manure loader	elmo		
unloading device	elmo	apu	stat
hoist, stationary, small crane	elmo	pneum hydr	stat
loading platform	pneum hydr		
Transportation			
truck	farm	contr	
tractor trailer	apu		
tractor load platform	apu		
fan	elmo	apu	stat
conveyor, pump	elmo	stat	apu
rail conveyor	elmo	hand	
fork truck	special	apu	
Snow plowing, Road scraping	apu	contr	

Abbreviations, see page 11

the "unusual" alternative. The table has been used as a basis for further discussions.

Some of the reasons that have influenced the choice of power source for the different operations may be given as follows:

Contractor units may be preferred for such operations which will be best performed by heavy, expensive, specialized implements, requiring considerable skill of the driver and an experienced crew, or if the operation is rare, e.g., drainage and earth moving. Contractors' units also may be used when the contractor can furnish the material involved, e.g., lime or fertilizer, spraying chemicals; or can take care of the material collected, e.g., potatoes, sugar beets, and grain. He then can have highly specialized equipment which can be used on many farms and, therefore, he can pay the high, initial costs of such implements. A condition also is that the distribution of lime, etc., or the harvest can be performed only once or twice a year and in a relatively short time on each farm. Contractors' units today often are built up around farm tractors. Their future development probably will carry them further away from the agricultural power unit as they become more specialized. They will not be included in this study in their most specialized form.

The farmers own implements are supposed to be used in all other cases. (Sometimes two or three neighbors may use one implement, but the implement still retains its character of a farmer's implement.)

For all operations where the implement is moving **in the field** when working, an independent, automotive, agricultural power unit (tractor) must be used. Electric tractors, connected by a cable to a power line, have been tried, e.g., in England, Russia, and Sweden, but have not yet proven practical for field work.

For all stationary operations, permanent or temporary, the electric motor should be considered as the first choice. It is very convenient to operate, takes up little space, gives no exhaust, and does not cause fires if properly maintained. It is easily started and stopped and is the most suitable type power (together with pneumatic or hydraulic motors) for automatic operations. When the power requirements are low, the electric motor always should be chosen. Large, electric motors require a high-voltage, three-phase supply system, which is not always available.

For a stationary operation where an electric motor, for some reason, cannot be used, an internal combustion engine or hand power must be used. When the operation shall not be made too often and does not have too long a duration and if the power requirement is high, the mobile power unit (tractor) may be used. Sometimes an old, outranged tractor--one that cannot be used for field work any longer--can be used. In most cases, however, a separate, internal combustion engine should be preferred as the best substitute for an electric motor.

In industry, pneumatic and hydraulic power has been used for a long time as a substitute for hand labor. It is used advantageously when power shall be applied on many places, e.g., for materials handling. The speed and the force of the action can be regulated easily and the components can be made very rugged. This possibility should not be forgotten when choosing a power system.

Chapter 2. Basic Parts of Field Operations where an Automotive Power Unit Is Used

From now on, only operations where an automotive power unit is used are discussed. Operations for special farms, for instance vegetable or fruit farms, are not included. These farms are often of another size than "ordinary" farms and they select their equipment from a different standpoint.

Many of the operations listed in Chapter 1 contain two or more basic parts, each performed by a distinguishable element of the implement. A field forage harvester contains, for instance, a pick-up element, a conveyor-feeder, a chopping element, and an elevating blower.

Often new machines have been designed by combining existing basic elements in a new way. Such new combinations appear much more often than entirely new basic elements do. When discussing the interference between implement and power unit, it therefore seems favorable to first study the elements and not the complete machine. Later, the combinations also should be considered.

The breakdown into elements can be made into smaller or larger units. I have tried to keep the elements as large as is possible with regard to the analysis.

Sometimes a basic part of a machine has had to be given the same name as the complete machine. For instance, in this connection "chopping" means just chopping and not the other functions a chopper usually also performs.

For each group of operations in the following tables, 105 - 114, it is first indicated how many operations could theoretically be performed by the same machine or unit. The criterion here is that the operations can theoretically be performed at the same time. Hay baling can be combined with raking, but not with tedding or cutting. Then are indicated the operations which are combined using our present machines and methods. A further discussion of the rules for combining operations is given in Chapter 3.

One earlier mentioned limitation of the study must be remembered here: only elements of machines commonly known today are considered. Also, operations which the author finds possible or impossible to combine might be considered otherwise by others.

Summing up the tables 101 - 103, we get the following list of separate groups of farming operations in which the automotive agricultural power unit is normally employed and for which a suitable power unit should be provided:

seed-bed preparation and planting (including all soil treatment up to the time of planting);

field work during the growing period;

harvesting;

loading;

transportation.

An analysis of these operations is given in Tables 105 - 113.

Occasionally the power unit will be used also for field improvement work and for some miscellaneous work, but these uses are not of such importance that they should influence the shape of the power unit. It might, however, be of interest to check how many of them could be performed by a power unit designed for normal operations. They are, therefore, listed in Table 114.

Tables 105 - 114. Basic Operations and Combinations of Operations.

In each table are listed all operations that can be performed simultaneously and, therefore, theoretically could be performed by a single (combined) unit. As a consequence, some operations are listed in connection with several main operations. Such duplication is indicated by a parenthesis around the name of the duplicate operation.

An operational unit is a combination of implements and one power unit such that all the implements can operate as they are mounted in the operational unit. In most cases, all implements operate simultaneously, but it also might happen that when some of the implements operate the others are idle but still connected to the unit; example: a self-propelled combine is an operational unit, the unloading auger is permanently mounted on the combine but is for most of the time idle.

A given set of operations usually can be performed by different sets of operational units. In the following tables, all operations in one table could theoretically be performed by a single operational unit. This alternative is indicated by a t (t_1, t_2, etc.). Other alternatives are called a, b, c,. . .

Some operations might not be included in all alternatives because they might not be needed at the same time as the other operations or in every case. The different operational units in an alternative are numbered 1, 2, ... The operations, performed by each unit, are indicated by a full, vertical line.

TABLE 105. TILLAGE, SEED-BED PREPARATION, AND PLANTING

			Combination in Operational Units					
			Theor.	Practically possible, examples			Customary, examples	
Alternative in Combining Operations			t	a	b	c	f	g
Number of Operational Units			1	3	4	3	11	5
Operation	Examples of Implements	Parts of Operation						
(Harvesting,	see 107 - 112 Harvesting)							
(Residue disintegration				3				
Manure spreading	Manure spreader, wagon and spreader	Storage, spreading	1	1	1	1	1	1
Subsoiling	Subsoil chisels or blades			2	2		2	
Deep tillage, 6-10 in.	Moldboard plows, disc plow, chisels, sweeps				3	2	3	[illegible]
Shallow tillage, 3-6 in.	Heavy cultivators, rotary tillers, vertical disc plow			3	4	3	4 5	3 4
Surface tillage, 1-4 in.	Light cultivators, harrows						6	
Listing	List plow, middle-buster							
Spreading of fertilizer and other chemicals	Fert. distributor, broad-caster, ammonia applier, band seeder	Storage, spreading		1			1	
Packing	Roller, tractor wheels, press wheels						5	5
Planting of main crop	Grain drill, broadseeder, corn planter, planting machine	Storage, distributing		3	4	3	7	
Planting of secondary crop (grass)	Grass-seeding attachment, grain drill	Storage, distribution					10	
(Finishing,	Press wheels, light harrow, roller,	see above)					11	5

TABLE 106. FIELD WORK DURING THE GROWING SEASON

			Combination in Operational Units									
			Theor.				Practically possible				Customary	
Alternative in Combining Operations			t_1	t_2	t_3	t_4	a	b	c	d	f	g
Number of Operational Units			1	1	1	1	1	1	1	1	3	3
Operation	Examples of Implements	Parts of Operation										
Thinning							/				/	
Cultivation	Row-crop cultivator, weed harrow, ridge plow		/									/
(Distr. of fertilizer and other soil chemicals,	see 105 Tillage and planting)					/	/		/	/	2	2
Chemical weed and insect control	Sprayer, dusting equipment, airplanes	Storage, pumping, fan, distribution									3	3
(Pasture maintenance	Mower, fertilizer distr., manure spreader, harrows, see 105 and 107)			/				/				
(Topping,	see 107 Green matter harvest)				/				/			

TABLE 107. HARVEST OF GREEN MATTER (GRASS, LEGUMES, CORN, ETC., FOR SILAGE OR DIRECT FEEDING)

			Combination in Operational Units					
			Theor.		Practically possible			Customary
Alternative in Combining Operations			t_1	t_2	a	b	c	f
Number of Operational Units			1	1	2	2	1	3
Operation	Examples of Parts of Machine	Parts of Operation						
Cutting	Cutter bar, flail type, rotating disc, corn head			1		1		
Chopping	Cylinder type, flywheel type, flail type	Feeding, chopping, elevating			1			1
(Loading,	see 114 Loading)		1			1	1	
(Storing,	see 113 Transportation)							2
(Hauling,				1	2	2		
(Unloading,	see 114 Loading)							3
(Seed-bed preparation,	see 105 Tillage and Planting)							
(Planting,								

TABLE 108. HAY HARVEST (STRAW HARVEST)

			Combination in Operational Units							
			Theor.	Practically possible			Customary			
Alternative in Combining Operations			t	a	b	c	f	g	h	k
Number of Operational Units			2	3	3	3	5	6	7	8
Operation	**Examples of Parts of Machine**	**Parts of Operation**								
(Cutting,	see 107 Green matter harvest)		1	1	1	1	1	1	1	1
Conditioning	Tedder, crusher	Pick-up, crushing, or tedding	1	1	1	1	1	2	2	2
Raking	Side-delivery rake, front rake, rear rake		2	2	2	2	2	3	3	3
Loading	Front loader, grass loader	Collecting, elevating			2	2				
Baling	Baler	Collecting, feeding baling	2	2			3	4	4	4
(Bale loading,	see 114 Loading)			2			3	4	4	5
(Chopping,	see 107 Green matter harvest)					2				
(Storing,	see 113 Transportation)		2	3	3	3	4	5	5	6
(Hauling,			2	3	3	3	4	5	5	6
Drying	Wagon dryer, barn dryer	Storing, hot air production, fan	2	3	3	3	4	5	6	7
(Unloading,	see 114 Loading)		2	3	3	3	5	6	7	8
(Seed-bed preparation,	see 105 Tillage and planting)		2							
(Planting,			2							

TABLE 109 SMALL GRAIN HARVEST

		Combination in operational units								
		Theor.	Practically possible						Customary	
Alternative in Combining Operations		t	a	b	c	d	e	f	k	m
Number of Operational Units		1	2	3	5	3	3	4	7	8
Operation	**Examples of Parts of Machine**									
Cutting	Cutter-bar, reel, flail	1	1	1	1	1	1	1	1	1
Windrowing										
Picking up								2		
Threshing	Cylinder, flail, fan							4		
Separating	Straw racks, cyclone	1					2			
Cleaning	Sieves, fan, cyclone		1	1	1	1			1	2
Grain storing	Tank, sacks							3		
Grain loading	Auger, sacks by hand or elevator							2		
(Grain hauling,	see 113 Transportation)			2	2		3	3	2	3
Grain drying	Wagon, stationary dryer	1	2	3	3	2			3	4
(Grain unloading,	see 114 Loading)			2	2		3	3	2	3
Straw chopping	Integral chopper, separate		1	1		1	2	2		
Straw baling	Integral baler, separate				4				4	5
(Straw storing,	see 113 Transportation)	1			5	3		3	6	7
(Straw loading,	see 114 Loading)				4	1		2	5	6
(Straw hauling,	see 113 Transportation)								6	7
(Straw unloading,	see 114 Loading)	1			5	3		3	7	8
(Seed-bed preparation,	see 105 Tillage and planting)									
(Planting,										

TABLE 110. CORN HARVEST FOR GRAIN

		Combination in Operational Units				
		Theor.	Practically possible			Customary
Alternative in Combining Operations		t	a	b	c	f
Number of Operational Units		1	2	3	4	5
Operation	Examples of parts of machine					
Husking		1	1	1	1	1
Shelling	Sheller, combine cylinder	1	1	1	1	3
Cleaning		1	1	1	1	3
(Storing)	Tank, wagon, truck	1	1	1	1	2
Loading	Auger		1	1	1	1
(Hauling, see 113 Transportation)		1	2	2	2	2
(Unloading, see 114 Loading)		1	2	2	2	2
(Drying, see 109 Small grain harvest)		1	2	3	3	4
Stalk shredding	Flail, rotating disc	1	1	1	4	5
(Seed-bed preparation, see 105 Tillage and planting)		1				
(Planting)		1				

TABLE 111. POTATO HARVEST.

		Combination in Operational Units				
		Theor.		Practically possible		Customary
Alternative in Combining Operations		t_1	t_2	a	b	f
Number of Operational Units		1	2	3	4	4
Operation	Machine or part of machine					
(Chemical stalk killing	Sprayer)		1		1	
Stalk shredding	Flail, rotary mower					1
Digging		1		1		
Separating	Conveyor, hand picker, stalk remower		2		2	2
Storing	Tank, wagon, truck			2	3	3
Loading	Elevator			1	2	2
Hauling, see 113 Transportation)				2	3	3
(Unloading, see 114 Loading)		1	2			
Grading, washing	Sorting machine, tank			3	4	4
(Seed-bed preparation, see 105 Tillage and planting)						
(Planting)						

TABLE 112. BEET HARVEST

	Combination in Operational Units					
	Theor.		Practically possible		Customary	
Alternative in Combining Operations	t_1	t_2	a	b	f	g
Number of Operational Units	1	1	3	3	6	5
Operation						
Top Shredding	1					
Top cutting		1		1	1	1
Top storing			1			3
(Top loading, see 114 Loading)					2	2
(Top hauling, see 113 Transportation)			2	1	3	3
(Top unloading, see 114 Loading)						
Beet lifting		1				1
Beet cleaning			1	2	1	
Beet storing						4
(Beet loading, see 114 Loading)					4	1
(Beet hauling, see 113 Transportation)					5	4
(Beet unloading, see 114 Loading)	1		3	3		
Taking sample		1			6	5
(Seed-bed preparation, see 105 Tillage and planting)						
(Planting)						

TABLE 113. TRANSPORTATION

Loads	Carriers
Heavy (2-6 tons) or voluminous (hay, straw)	Wagons, trucks, (ev. tanks or bins on implement)
Light, not voluminous	Tanks or bins on implement, loading platform on power unit, hand carts, wagons, trucks

Stationary or portable, horizontal conveyors or pipelines are not used very much for field work. They usually do not use a power unit of the kind discussed here; therefore, they are not included in the study.

It should be remembered that considerable transportation is included in many of the operations listed earlier.

Parts or Operation	Combinations in One Unit		
	Theoretical	Practically Possible	
	t	a	b
Hitching carrier to power unit	]	]	]
Placing carrier in position for loading	]	]	]
(Loading, see 114 Loading)	]		
Hauling	]	]	]
Parking carrier	]	]	]
Adjusting position of carrier	]	]	
(Unloading, see 114 Loading)	]	]	]

TABLE 114. LOADING

Material Loaded or Unloaded	Loaders
Bulk material, light, fibreous: hay, straw, grass,	Continuous loaders, grass loaders, front loaders, by hand
Bulk material, light, granular: grain, feed	Continuous loaders, augers, by hand
Bulk material, heavy: sand, gravel, dirt	Front loaders, loading machines, excavators
Small sized or light pieces: potatoes, beets, haybales, strawbales	Continuous elevators, front loaders, by hand
Heavy pieces: sacks, boxes, barrels, logs, stones	Front loaders, loading machines, cranes

Unloading

Dumping devices	Wagon bottoms
Elevators	False ends
Front loaders	Cranes

Parts of Operation

Gathering	Picking up
Elevating	(Storing)
Carrying	Dumping

Chapter 3. Combinations of Operations

As a general rule, it is most efficient to perform as many operations as possible at the same time, instead of performing them one at a time in a sequence. The energy to propel the power unit over the field is needed every time the operating unit passes the field, independent of the number of operations performed. The total energy needed therefore is higher for a split operation than for a combined operation. The same holds true for the compaction caused by the wheels and for the operator's time. Consequently, the total cost and the total time for a split operation is higher than for a combined. (In a few cases, the truth of this statement is not immediately obvious, but the contrary is never true.) The trend therefore should be to combine as many operations as possible. The theoretical limit for such combinations in indicated in Tables 105 - 115.

This limit, however, in many cases, can be neither reached nor approached for practical reasons. Some of the reasons are:

1. A combination of too many functions makes the unit very clumsy, difficult to handle, and difficult to support on soft ground. Nor might the work force on the farm be large enough to operate it.
2. The reliability becomes lower, or in other words, the time lost for repair and adjustment becomes greater when many functions are combined. If the reliability of a single function is p (a number between 0 and 1),

the reliability of a combination of n such functions is only p^n, which always is lower than p. (Ref. 1). This multiplication of reliabilities is especially serious when a function with low reliability is added to a machine, e.g. a straw baler to a grain combine. The relatively unimportant straw baling slows down the more important grain harvest.

3. The timeliness factor. A certain operation A might be most efficiently performed during a given short period of time. A given power unit can handle a corresponding implement A with the capacity of a acres/hour. If another operation B is added, and B demands more power so that the capacity for B + A is only b acres/hour, b being less than a; the time for completing operation A (and B) is b/a times the time for A alone, i.e. longer than this time. If this time is longer than the favorable period, the combination has resulted in a poorer final result of operation A, which should not be tolerated. Examples of such time-sensitive operations, A, are planting and harvesting. They should not be combined with "slow" and power-consuming operations unless the machine capacity is large enough and the acreage small enough to ensure that the work is finished in proper time. Knowledge about the timeliness factor is necessary, therefore, when calculating the merits of combinations of operations (and also when determining the optimum

size of a single implement). More research in this area should be done. For some values, see Barnes-Link. (Ref. 3). An indication of the time available for each operation is given in Tables 201 - 205.

4. The field efficiency (defined by e.g. Bainer, (Ref. 1), p. 25) is usually lower for a combination than for the same implements used alone. Nothing is, however, known about the size of the reduction.

In Tables 105 - 114, some combinations of operations are indicated as "practically possible" with due regard taken to the factors mentioned here. For lack of numerical values, no analytical test of how "practical" they are has been made, but only subjective appraisals.

Chapter 4. The Relative Importance of the Different Field Operations

As long as the aim is to design a separate power unit for each implement or, in other words, to make self-propelled implements, the only reason to consider the importance of the implement in question is to estimate the future demand for it. When, on the other side, the power unit shall be used for several operations, their relative importance ought to be known because, thereby, it will be possible to decide how much consideration should be given to the different--probably conflicting--requirements from the operations. If the power unit shall be used for all operations, this is really important and might be the hardest problem of all to solve.

There are many ways of defining importance in this case. One of the most apparent is the duration of the operation, which gives the size of the operation, e.g. in hours/year or better in acres/year. A frequency measure is how often the operation is performed, e.g. in times per year or times per week. More difficult to express in figures are such measures as the value of the product involved in the operation, or the importance of the operation from the standpoint of it having to be performed at a fixed time or if it can be postponed or excluded without any great disadvantage.

There are two ways of finding these measures of importance. One is to analytically study the work schedule of theoretical farms with assumed acreages of different crops. The acreages to be covered can then be calculated and from there the duration of the operation by assuming a given capacity of the outfit. This procedure makes it possible to investigate future, improved types of farming. An attempt in this direction is made on pages 33 - 40

The other method is to statistically study the operations on existing farms. Correctly made, such a study should be able to give information that can be used in the future. The main advantage with this method is that it gives more accurate values for the waste time (field efficiency) than the analytical method. The extent of such operations as transportation also is very difficult to estimate analytically.

A summary of statistical investigations on the time used by the tractor(s) for different operations is given in Table 120.

An Analytical Determination of the Duration and Frequency of Farming Operations with an Automotive Power Unit Involved

There is an almost innumerable number of types of farms, but the analysis must be limited to a few which might be called type farms. In reality, there might not be many farms exactly like the type farms, but for this purpose, the type farms could probably be made to agree close enough to a great number of real farms. In describing the type farms, more consideration is given here to conditions as they are on advanced or even future farms in the group than as they are as an average.

Six type farms are described in Table 121 and the operations involved for each crop are described in Table 122. The final result as to duration and frequency of the different operations on these six type farms is given in Table 123.

TABLE 120. ACTUAL USE OF POWER UNITS AND IMPLEMENTS.

1. USA. According to Brodell (ref. 8). 1941. Only tractor-driven implements.

	Hours/year Average	Limits	Quantities
Manure spreading	142	25-1000	177 tons/year
Row-crop planter, 2-row	76	20-250	131 acres/year
- " - , 4-row	80	20-250	262 -"-
Grain drill	79	20-500	201 -"-
Mower	78	20-500	154 -"-
Binder	55	20-350	100 -"-
Combine, less or equal to 6 ft	110	25-400	126 -"-
-"- , wider than 6 ft, less than 10 ft	126	25-400	207 -"-
-"- , 10 ft or wider	143	25-400	400 -"-

2. Sweden. According to Jeppsson (ref. 16). Tractor size around 30 belt hp. One horse used for some light work. Calculated use for a given farm.

Plowing	26 %	of total tractor time
Cultivating	10 %	- " -
Fertilizer spreading	7 %	- " -
Planting	6 %	- " -
Binder	7 %	- " -
Forage harvesting	5 %	- " -
Transportation	35 %	- " -

3. Sweden. According to Berglund-Karlson (ref. 6). 1953. General type of farm.

	Average	Limits
Farm size, acres	53	32-80
Tractor size, belt horsepower	25	16-40
Other field power (x)	1 horse, used for rolling, fert. distr., planting, transportation.	

TABLE 120. Cont.		Average	Limits
Field work, total, Hours/acre		5.2	2.8-7.5
plowing	-"-	1.8	0.6-3.4
cultivating	-"-	1.7	0.8-3.4
rolling (x)	-"-	0.2	
fertilizer distr. (x)	-"-	0.2	
Planting (x)			
Mower	-"-	0.5	0.1-1.3
Binder	-"-	0.6	0.1-1.4
Other field work	-"-	0.2	
Transportation (x)	-"-	2.8	0.4-6.9
Belt work	-"-	0.2	0-1.4
Miscellaneous	-"-	0.3	0-1.9

Basis for area indication is total farmland acreage.

(x) indicates use of other power source than tractor.

4. West Germany. According to Schilling (ref. 28). (Figures taken from graph.)

	Farm size, acres 35 - 250	
Tillage	7-26 %	of total tractor time
Planting and care of plant	18-16 %	- " -
Harvesting	20-20 %	- " -
Transportation	51-37 %	- " -
Belt work	4-1 %	- " -

TABLE 121. MAJOR CROPS FOR DIFFERENT TYPES OF FARMS, EXAMPLES.

Figures taken from an unpublished report (ref. 25), based on 1954 Census of (US) agriculture (ref. 10). Types and economic classes according to the Census.

Type of farm	State	Area no.	Size of farm 3/, acres: Total	Size of farm 3/, acres: Cropland	Crops, per cent of cropland 1/: Small grain 2/	Corn grain	Soy-beans	Corn silage	Hay	Sugar beets	Cattle, heads	Tractors/farm 3/
General	Mich.	49	125	90	30	20		0	20	10	15	1.57
Dairy	Wisc.	65	115	75	25	15		10	30		25	1.64
Dairy	N. Y.	7	180	80	15			10	60		30	1.20
Cash, small grain	N.Dak.	90	550	400	65 4/							1.70
Cash, corn	Ill.	63	125	100	30	40	25				10	1.66
Livestock, hogs	Iowa	71	200	100	25	30	20	5	15		30	1.32

1/ Only major crops. The sum of indicated percentages is therefore less than 100. These percentage figures are the same for larger farms, e.g. in class II.

2/ Small grain = wheat, oats, barley, flaxseed.

3/ For economic class IV (5000-2500 gross sale/year). For class II (25000-10000) the acreage and the number of cattle is about twice as large as indicated for class IV and the number of tractors on each farm 50-75 % greater. Figures rounded.

4/ Plus around 20 % summer fallow.

TABLE 122. SIZE AND FREQUENCY OF THE OPERATIONS FOR SOME MAJOR CROPS.

Operation	Area covered for every 100 acres grown of									Times a year operation is performed 1/
	Small grains	Grain corn	Soy-beans	Corn silage	Hay	Grass& clover silage	Sugar beets	Potatoes	Fallow	
Plowing	85	100	100	100	-	-	100	100	(100)	5
Cultivating, harrowing	200	200	300	200	-	-	300	200	400	7
Rolling	0	0	100	0	0	0	50	0	100	2
Fert. at planting	100	100	100	100	-	-	100	100	-	1
Planting	100	100	100	100			100	100	-	(3 grain drilling) 3/
Row-crop cultivating	-	150	200	150	-	-	300	300	-	4
Fert. after planting	60	75	0	75	100	100	100	100	-	2
Spraying	100	100	0	100	50	50	0	500	-	(5 potatoes) 3/
Manure spreading 2/	100	100	80	100	0	0	100			200 - 300
Harvesting main crop	100	100	100	100	200	200	100	100		(4 or 100 mowing) 3/ (1 or 75 forage harvesting) 3/
Harvesting secondary crop	0 to 100						0			

Explanations, see next page.

Explanations to table 122

Figures estimated after discussion with Mr. Clarence Hansen, Michigan State University.

1/ An operation interrupted before finishing for such reasons as shortage of labor or power units, which are not inherent in the operation as such, is considered performed only once. An operation is consider performed more times if it has to be repeated at another season or time, e.g. early or late fall plowing and early or late spring plowing.

2/ This area limited by the amount of manure available.

3/ In other cases than the one, indicated in brackets, the operation is performed only once a year.

TABLE 123. ACREAGES COVERED YEARLY IN OPERATIONS ON FARMS OF DIFFERENT TYPES.

Based upon tables 121 and 122 and consequently referring to small to medium sized farms. The acreages are calculated for the major crops, which use 80-95 % of the total cropland, and then extrapolated for the total cropland acreage. The figures are rounded.
The figures for small grain, cash crop farms, are adjusted downwards slightly on account of the special conditions for this type of farms. For the other farms part-time fallow is included, = 10 % of cropland acreage.

Operation	Type of farm and acres cropland					
	General, Michigan	Dairy, Wisconsin	Dairy, New York	Cash, small grain, N. Dakota	Cash, corn, Ill.	Livestock hogs, Iowa
	90	75	80	400	100	100
	Acres covered yearly					
Plowing	60	45	20	330	100	80
Cultivating	200	130	85	1000	225	225
Rolling	10	10	10	100	40	30
Planting, drill	45	25	15	300	30	25
" , planter	20	20	10	0	70	60
Fert. after planting	70	60	70	180	50	60
Row-crop cultiv.	70	35	15	0	120	100
Spraying	70	60	50	300	75	65
Mowing	45	55	110	0	0	30
Forage harvesting	0	10	10	0	0	5
Combining	35	25	15	300	60	45
Corn harvesting	20	15	0	0	40	30
Baling, hay, straw	55	80	125	0	0	40

The result is given as area covered per year. In order to get a figure for hours per year, we have to divide by the field capacity of the implement. This is given for some machines in Tables 210 - 215, and also can be found by multiplying speed, working width, and field efficiency. Field efficiencies are given in Tables 210 - 215.

A more thorough study of type farms and their relative importance would be desirable, but the figures given here might be sufficient for the calculations in following sections.

In the future, farm size will increase and the number of crops on each farm will decrease, but these changes will take place slowly only. The figures for the crop acreages on a farm can, therefore, be used possibly for a long time.

SECTION II. CHARACTERISTICS OF IMPLEMENTS AND THEIR OPERATION OF IMPORTANCE FOR THE POWER UNIT

Chapter 5. The Requirements of the Implements Are the Most Important Factors Determining the Power Unit Design

With a few early exceptions of almost experimental character, the development of the mechanical power unit has gone along the lines of making a machine which could be a substitute for the horse and, therefore, which could use implements of the same design as when the horse was the sole power source. This mainly was due to the fact that the transition to the new power unit had to proceed gradually with the old and the new power unit being used alternately. Because the horse could not be adjusted to the implement, the implements had to be designed for the horse.

This transition period now, however, should be considered past in the highly mechanized countries, the mechanical power unit there being the only one. The implements now can be redesigned to make full use of the possibilities a mechanical power unit can give. At the same time, the power unit can be transformed from being a mechanized horse to better complying with the requirements of the new implements.

Logically, the best-working outfit should be found when the design is based upon the requirements of the implement; the implement is the productive, primary part of the combination and the power unit the secondary, essential, but unproductive part.

Therefore, the requirements of the implement must be of primary interest and the design of the power unit, as far as possible, adjusted to them.

The self-propelled implement can be built to satisfy the functional demands of the working parts as closely as possible and should, therefore, be the best design. Lately, we also have seen an increasing popularity of some self-propelled implements--when the farmers want a machine with high capacity and good operational efficiency.

Chapter 6. The Requirements of the Implements

The requirements of the implements can be classified as operational and technical. Operational requirements may be considered requirements on working speed and speed adjustment, on height adjustment, accuracy of steering, supervision needed, position of implement relative to the wheels of the power unit, quantities to be handled, field conditions, etc. Operational requirements usually are determined by other factors than the implement itself and do not change with the design of the implement. They will be different for different farms, areas, or countries, but they will not change at all, or at the most very slowly, with time.

Technical requirements or descriptions may be classified as draft and power requirements, weight, center of gravity, outer dimensions, etc. The technical requirements may differ considerably between different existing designs and also will change as new designs are developed. Because speed is very often limited by the design of the machine instead of by factors in the operation, it will be considered together with technical requirements.

Many of the figures in the following tables on requirements will be given relative to a certain capacity. The capacity may be considered the independant variable in the case. When several elements work together, their capacity should, of course, be the same. However, capacity also plays an important role in the decision of which elements or implements should be combined for simultaneous work. Furthermore, there ought to be some matching between the capacities of implements used at different times but in the same enterprise, especially for economic reasons. These two questions about matching and combining implements which both influence the power unit design have been discussed in Chapter 3 and will appear again in Section IV.

In Chapter 2 there was introduced the concept of elementary parts of operations and implements. This breakdown is also useful when listing the requirements of the implements because different elements have different requirements. To refer to all these as requirements of the complete machine would be to introduce them also for elements, for which they do not apply and would make it more difficult to find a good solution.

Comments on Tables 201 - 206 Operational Requirements

Field conditions have to be described by words. It would have been much better to give soil values but such are not yet available.

Time available for operation gives an indication of the importance of the operation as discussed in Chapter 3. The following scale has been used: plenty, enough, limited, short, very short.

Supervision of function given by the driver when the implement is working, is classified according to the scale: continuously, often, occasionally, none. When continuous supervision is deemed needed, the part of the implement which needs particular attention is sometimes mentioned.

<u>Adjustments of implements in work</u>: Adjustments besides height control and steering.

<u>Height control of implements in work</u>

none = implement working at fixed height

preset = height determined by gauge wheel, shoe, etc., adjusted beforehand in <u>fixed</u> position relative to the implement.

manual = manual change of working height

automatic = change of height is or could be performed automatically by devices in implement or power unit.

<u>Height control of implements on headlands</u>

none = no change in height needed

mech. lift = implement must be lifted

automatic = implement is or could favorably be raised by devices which sensed the end of the land and automatically lifted.

<u>Accuracy of steering of implement in work</u>. Scale: none, fair, good, high, very high.

<u>Steering of power unit in work</u> as imposed by the implement in question:

none = implement works or could work stationary

manual

automatic = power unit is or could favorably be steered automatically in this operation. ( ) indicate alternative might be questionable.

automatic and manual = additional manual fine steering needed.

<u>Type of container</u> for (loading and) transportation (table 206)

platform: only a bottom

closed: bottom and sides

tight: bottom and sides tight

TABLE 201. OPERATIONAL REQUIREMENTS. TILLAGE, SEED-BED PREPARATION AND PLANTING OPERATIONS.

Operation Implement	Field conditions.	Quantities of product involved a/ lbs/acre	Time available for operation.	Supervision of function	Adjustment of implement in work.	Height control of impl. In work	Height control of impl. On headlands	Accuracy of steering of implement in work	Steering of power unit in work.	Factors, affecting position relative to power unit wheels, other implements, etc.
Subsoiling	Dry but sometimes loose		Plenty	None	None	Preset	Mech. lift	Fair	Manual	None
Deep tillage plows	Fall: slippery Spring: soft but dry		Enough Short	Occasionally	Occasionally	Automatic	Mech.(autom) lift	Good	Automatic	Usually no wheeltracks on plowed land
Shallow till. heavy cult. disc plows	Usually dry, uneven, loose		As above	None or occasionally	None or occasionally	None	Mech. lift	Fair	Manual	No or only light wheeltracks on cultivated land
Surface till. harrows	Dry, loose		As above	None or occasionally	None	None	None	Fair	Manual	As above
Listing	Dry, loose		Enough	None	None	Automatic	Mech.(autom) lift	Good	Automatic	Tread adjusted to row width
Manure spreading	Good to soft and slippery	12000 - 27000	Every day plenty	Occasionally	On-off	None	None	Fair	Manual	Spreading behind, if possible
Spreading of fert. and chemicals	Dry, loose or soft	100 - 300- -700 each time	Enough	Same	On-off	None	None	Good	Manual	Spreading behind, if possible
Packing	Dry, loose		Enough	None	None	None	None	Fair	Manual	
Planting of small grain	Dry	155 - 200	Short	Often (opener&hopper)	On-off	Preset	Mech.(autom) lift	High	Manual (autom.)	Wheeltracks ought to be erased before planter
corn	Dry		Short	Often (mech.&hopper)	On-off	Preset	Mech. lift	Very high	Manual (autom.)	Tread adjusted to row width wheels either in every row or between rows
beet seed	Dry	4 - 20	Short	Often (opener&hopper)	On-off	Preset	Mech. lift	Very high	(Autom.) Manual	Tread adjusted to row width
potatoes	Dry	800-2700	Short	Often (mech.&hopper)	On-off	Preset	Mech. lift	High	Automatic	Tread adjusted to row width
grass seed	Dry	20 - 30	Enough	Often (hopper)	On-off	None	None	Good	Manual	
Transplanter	Wet or dry			Continuously	Crew	Preset	Mech. lift	High	Automatic	Tread adjusted to row width

a/ Ref. 1 p. 239, 250, 283, 286. Ref. 18 p. 9:13, 9:15, 9:19, 10:13, 11:7, 12:9, 13:16, 14:32

TABLE 202. OPERATIONAL REQUIREMENTS. FIELD OPERATIONS DURING THE GROWING SEASON.

Operation	Field conditions.	Quantities of product involved */ lbs/acre	Time available for operation	Supervision of function	Adjustment of implement in work.	Height control of impl. in work	Height control of impl. on headlands	Accuracy of steering of implement in work.	Steering of power unit in work.	Factors, affecting position relative power unit wheels, other implements, etc.
Thinning	Dry, firm		Limited	Continuously (mechanism)	None	Preset	Mech. lift	High	Automatic	Row width determines tread
Row cultivating	Dry, firm		Limited	Continuously	None	Preset	Mech. lift	Very high	Automatic & manual	Row width determines tread. No wheeltracks left behind. Sometimes high clearance.
Spraying	Usually dry, firm	40-1700	Very short	Occasionally	On-off	Preset	None	Good	Manual (automatic)	Row width. Spraying if possible behind machine. High clearance.

*/ Ref. , p. 482

TABLE 203. OPERATIONAL REQUIREMENTS, HARVESTING OF GREEN MATTER, HAY AND SILAGE.

Operation	Field conditions.	Quantities of product involved */ lbs/acre	Time available for operation	Supervision of function	Adjustment of implement in work.	Height control of impl. in work	Height control of impl. on headlands	Accuracy of steering of implement in work.	Steering of power unit in work.	Factors, affecting position relative power unit wheels, other implements, etc.
Harvest of green matter.										
Cutting	Dry or slightly wet. Sometimes soft.		Enough	Often	None	Preset	Mech.(autom) lift	Good	Automatic	Tread related to width of cut. No driving in the uncut. If possible front cutting.
Chopping	As above	15000 - 40000	Enough	Occasionally	On-off Chute steering	Preset	Mech.(autom) lift	Good	Automatic	As above. Centered position desirable.
Hay harvest										
Picking up	Dry, firm	2000 - 7000	Short	Occasionally	None	Manual	Mech. lift	Good	Manual (autom)	No or few wheeltracks in front of pickup. Material sometimes swathed.
Conditioning	Dry		Short	Occasionally	On-off	(Preset) Manual	Mech. lift	Good	Manual	Behind cutter-bar. No heavy wheeltracks in the conditioned material.
Raking	Dry, firm	3000 - 5000	Short	Occasionally	None	Preset	Usually none	Fair	Manual	Swath undisturbed. High clearance. Front position desirable.
Loading w. contin. loader	Dry, firm	3000-5000--7000 (half-dry)	Short	Often or continuously	Distributing in wagon	Preset	Usually none	Good	Manual (autom)	Few wheeltracks in the unloaded. Wagon easily hitched in good position.
Baling	Dry, firm	3000 - 5000	Short	Often	On-off Bale-loading	Preset	Usually none	Good	Manual (autom)	Centered if possible. Few wheeltracks in unbaled. Wagon easily hitched in good position.
Drying	Dry, firm	4000 - 7000	Limited	Occasionally	Check humidity	None	None	None	None (stationary)	Easy exchange of storing space (platform) desirable.

*/ Ref. 1, p. 318 Ref. 18, p 14:32, 16:3, 16:6

TABLE 20b. OPERATIONAL REQUIREMENTS. GRAIN HARVEST.

Operation / Implement	Field conditions	Quantities of product involved e/ lbs/acre	Time available for operation.	Supervision of function	Adjustment of implement in work	Height control of impl. In work	Height control of impl. On headlands	Accuracy of steering of implement in work	Steering of power unit in work.	Factors, affecting position relative to power unit wheels, other implements, etc.
Small grain harvest										
Cutting	Dry, sometimes soft	6000 - 12000	Limited	Continuously	Adjust reel	Automatic continuous	Mech.(autom) lift	Good	Automatic	Front-cutting desirable. No wheeltracks in uncut.
Windrowing	As above	6000 - 12000	Limited	Continuously	Adjust reel	As above	As above	Good	Automatic	As above. Clearance for swath.
Picking up	Dry, sometimes soft	6000 - 12000	Limited	Continuously	None	Preset	Mech. lift	Fair	Manual (automatic)	Tread related to swath distance
Threshing	Dry, sometimes soft	6000 - 12000	Limited	None	None	None	None	None	None	Close to cutting or pick up device
Separating	As above	2000 - 6000		None	None	None	None	None	None	Close to threshing device
Cleaning	As above	3000 - 7000		Occasionally (final product)	Occasionally	None	None	None	None	Levelling needed on hilly land
Grain storing (tank)	As above	2000 - 5000		Occasionally	None	None	None	None	None	
Grain loading	As above	2000 - 5000	Short or very short	Often	On-off	None	None	None	None	Outlet in good position for loading wagon
Grain drying	(As above)	2000 - 5000	Limited	Occasionally	On-off	None	None	None (stationary)	None	Change of heater-fan unit or grain box should be easy
Straw chopping (integral)	Dry, sometimes soft	2000 - 8000	Limited	Occasionally	None	None	None	None	None	Close to separating unit
Straw baling (integral)	As above	2000 - 8000	Limited	Often	Dumping or loading bales	None	None	None	None	Loading of bales should be easy or bales dropped beside machine
Grain corn harvest										
Picking	Sometimes soft, slipp.		Enough	Continuously	None	Some, automatic	Mech. lift	Good	Automatic	In front of machine
Husking	As above		Enough	Some or none	None	None	None	None	None	Close to picker
Shelling	As above		Enough	None or some	None	None	None	None	None	Close to picker
Cleaning	As above	4000 - 6000	Enough	Occasionally (end product)	Some occasionally	None	None	None	None	Close to sheller
Stalk shredding	Sometimes wet & soft		Enough	None	On-off	Some, manual	Mech. lift	Fair	Manual	

e/ Ref. 1, p. 422, Ref. 18, 9:16, 9:19, 10:13, 10:18

TABLE 205. OPERATIONAL REQUIREMENTS, HARVESTING OF ROOT CROPS.

Operation	Field conditions	Quantities of product involved */ lbs/acre	Time available for operation	Supervision of operation	Adjustment of implement in work	Height control of impl. In work	Height control of impl. On headlands	Accuracy of steering of implement in work	Steering of power unit in work	Factors, affecting position relative to power unit wheels, other implements, etc.
Potato harvest										
Digging	Sometimes wet & soft	12000 - 30000	Enough	Almost continuously	None	Occasionally Manual	Mech. lift	Good	Automatic	Tread determined by row width for multi-row digger
Separating	As above	12000 - 30000	As above	Occasionally or continuously (hand picking)	On-off (Handpicker)	(Hillside compensation)	None	None	None	Close behind digger (Room for hand pickers)
Storing (tank)	As above	12000 - 30000	As above	Occasionally	None	None	None	None	None	
Loading from machine	As above	12000 - 30000	Short or enough	Almost continuously	On-off Adjusting chute	Adjusted to wagon, autom. or manual	None	Good	Automatic	Outlet in good position for loading. As little handling as possible
from ground	Mostly dry but soft	12000 - 30000	Limited	Continuously	Adjusting chute	Manual, occasionally	Mech. lift	Good	Manual	As above
Grading, washing	Sometimes wet, soft	12000 - 30000	Enough	Almost continuously or continuously (hand sorting)	(Handpicker)	None	None	None	None (usually stationary)	
Sugar beet harvest										
Top cutting	Often wet soft		Limited	Continuously	None	Automatic	Mech. lift	High	Automatic and manual	Tread determined by row width for multi-row machine
Top storing	As above	15000 - 20000	Limited	Continuously	Emptying	None	None	None	None	Deposit tops to side of machine
Beet lifting	As above	30000 - 60000	Limited	Continuously	None	Preset	Mech. lift	High	Automatic and manual	Tread determined by row width for multi-row machine
Beet cleaning	As above	30000 - 60000	Limited	Occasionally	None	None	None	None	None	
Beet storing	As above	30000 - 60000		Occasionally	(Emptying)	None	None	None	None	Outlet in good position for loading
Taking sample	As above	150 - 200	Short		Changing bags	None	None	None	None	Sample taken at loading. Dirt content = average cont.

*/ Ref. 1 , p 453. Ref. 18 , p. 12:5, 13:16

TABLE 206. OPERATIONAL REQUIREMENTS, TRANSPORT AND LOADING OPERATIONS.

Material	Quantities a/ lbs/acre	Quantities a/ lbs/load	Volume weights**/ lbs/cuft	Type of container	Times a year	Field (road) conditions	Device for loading	Device for unloading	Other requirements
Hay, straw	-5000								
loose		-10000	4	Platform	5	Dry and firm	Direct Contin. load. Frontloader	Hoist Elevator	Behind driver in transport
baled		-10000	10-12	Platform	5	Dry and firm	As above By hand	As above By hand	As above
chopped		-10000	3.5-8	Closed	5	Dry and firm	Direct	Self-unload. wagon	Roof usually needed Behind driver in transport
Grass	-40000								
loose				Closed or platform	2 or 150	Sometimes wet and soft	Direct Contin. loader Frontloader	By hand Self-unload. wagon	Behind driver in transport
chopped		-11000		Closed	2 or 150	As above	Direct	Self-unload. wagon Dumping	Behind driver in transport
Silage, corn		-11000	20-23	Closed	1 or 75	Sometimes wet and soft	Direct	As above	As above
Grain	-5000								
loose		-17000	30-53	Tight	2	Sometimes soft	Direct	Dumping Self-unload. wagon	
sacks				Platform	1	Sometimes soft	By hand Hoist Elevator	By hand Frontloader Elevator	
Potatoes	-30000								
loose			44	Closed, special	1	Sometimes wet and soft	Direct Elevator	Built-in unloader	Very gentle handling needed. If possible remove dirt
barrels				Platform	1	As above	Elevator Frontloader By hand	By hand Hoist Conveyor	
Sugar beet	-40000	-17000		Closed	1	Often wet and slippery	Direct Elevator	Dumping	If possible remove dirt
Feed, ground				Tight	-300	Roads; sometimes slippery	Auger Conveyor	Auger Dumping	Mixing device often included
Sand, gravel dirt		-80000	70-120	Tight	-3-80	Sometimes loose, slippery	Frontloader By hand Excavator	Dumping By hand	Spreading device sometimes added (icy roads)
Milk cans, fence poles, spare parts, fuel, etc.		-1000		Platform or closed	50 - 1000	Any	Loading platform By hand	Loading platform By hand	Shall not prevent hitching implements
Logs				Platform	0 -10	Sometimes soft and slippery	By hand Cranes Frontloader	By hand Dumping Cranes	Often very difficult roads Load secured.
Stones		-7000		Platform	0 - 5	As above	Frontloader Cranes	Dumping Frontloader	Load must be secured in transport
Workers to the field		1 & 2		Seats	50 - 2000	Any			Safe, convenient and sheltered
Manure	-27000			Closed	3 - 300	Sometimes soft and slippery	Frontloader Direct	Spreader Self-unload.	
Fertilizer	-1000			Tight or platform	5	Usually dry but sometimes soft	Elevator By hand	Spreader By hand	
Lime	-18000			Tight	1	Dry but sometimes soft	Conveyor	Spreader	

*/ Ref. 1 , p. 283, 286, 287. Ref. 18 p. 14:32, 16:3, 16:6, 9:16, 12:5

**/ Ref. 1 , p. 330, 362, 347. Ref.18p. 9:19, 10:19, 13:16

Comments on Tables 210 - 215. Technical Requirements

Speed limited by:

function = the limit is inherent in the soil or the crop, mostly being caused by the sensitivity or the inertia of the particles.

field = the evenness of the field or road

machine = a redesign of the machine would permit higher speeds

power = enough pull or power not available for higher speeds

Pull and power: Power means here other power than the pulling force or draft. Implements with no power-driven parts will therefore be indicated as requiring only pull, no power.

Pull caused by rolling or sliding resistance to wheels, shoes, etc. carrying the weight of the implement and of the product on it is included in the pull when there is a useful pull, also, caused by the action of the implement on the soil, etc. When the pull is only parasitic, being caused only by the weight-carrying wheels, it is not indicated because the weight can perhaps be partly transferred to the power unit and utilized. Further studies are needed to show what part of the pull is useful and what is parasitic. For examples, see Chapter 8. The pull, caused by grade is not included, but should be remembered. Power for ground-wheel-driven mechanisms is counted as power, not as pull. The figures given refer to horizontal pull. The vertical pull that can or must be exerted on the implement is also important. With some exceptions, as e.g. disc plows and harrows, grain drill openers and cultipacker, the maximum allowable vertical pull is of the same size as the weight of implement. Knowledge about the vertical forces would be of great value when designing the power unit, but very few investigations give any information about these. The figures given for pull and power in the tables should be considered only as rough information about their order of magnitude. They should not be used directly when making a design. Instead a survey of original investigations should be made in order to find out their real nature. The pull and power needed can sometimes be changed considerably by changing the design. For natural reasons these variations cannot be described here, but a list of references is given in the tables. References, listed in (ref. 1) are not listed again here. Bainer (ref. 1) has on pages 116-138 and 548-549 given a general discussion, some figures and general references. The power and pull figures should be related to some basic quality of the material, e.g. soil values, moisture content, etc. Thereby, it would be possible to reduce the variations in the figures for each individual case.

<u>Power type</u>: Way of transmitting power from the power unit to the rotating parts of the implement. "None 1" means that power driven parts are not used now, but might be used in the future.

<u>Weight and dimensions</u>: Weight and dimensions are given for the whole part of the implement, including transmissions and adjustment devices for this part. The dimensions of the working parts inside it are smaller. Carrying wheels, outside frames, engines or driver's platforms are as far as possible excluded.

<u>Minus-sign after weight</u> means that weight of wheels, etc. is included in the figure. Two minus-signs indicate that weight of heavy parts such as an auxiliary engine is also included. <u>Minus-sign after length</u> indicates that length of the drawbar, etc. is included. When possible, the weight is given per foot working width. This is indicated by a "1" in the size column. The width is then sometimes given as w + 00 which indicates how much wider the implement is than the working width.

<u>Size</u>: Size has as far as possible been given as feet nominal working width. For implements with optional working widths, as e.g. combines, the smallest width has been chosen as representative, because it is the width for the highest producing fields.

TABLE 210. TECHNICAL REQUIREMENTS. TILLAGE, SEED-BED PREPARATION AND PLANTING.

Field efficiencies: 8/ 75 - 90 % for tillage
70 - 85 % for drill planting
50 - 65 % for checkrow planting

Implement	Capacity acres/hr/ft 1/	Present max.size ft 2/	Speed range mph 3/	Speed limited by	Pull per ft width lbs 4/	Power type	Weight and dimensions 5/				
							Size ft	Weight lbs	Length inch	Width inch	Height inch
Moldboard plow ord. depth	0.3-0.45	8 x 16 in = 11 ft	2.5-5(6)	function &machine	500-1200	None?	1	220to300	50/bott	21/bott	30
Disc plow ord. depth	0.3-0.4		2 -(5)	function	500-1000	None?	1	300to1200			
Shallow plowing	0.3-0.45	20	4 - 5	function	150-350	None?	1	150to600			
Subsoiler			0.5-(4)	power?		None?					
Cultivator heavy	0.25-0.35		2-5.5(7)	function	90 - 160	None	1	150			
Lister middlebuster		17	2-(5.5)	function	150-350						
Disc harrow	0.25-0.35	20(36)	2.5-4(7)	function	40 - 225		1	125to190	54		22
Spring teeth harrow	0.25-0.35	22	2 - (7)	function	75 - 150	None	1	40 to 60 to 100			
Spike teeth harrow	0.25-0.35	24	3-5(10)	function &machine	30 - 60		1	20 to 25			
Rotary hoe		42			30 - 85		1	50 to100			
Rotary tiller 7/		8	0.8-2.5	power		Mech.					
Roller, packer	0.2-0.4	17	1.3-5	function	30 - 60	None?	1	110			
Manure spreader		135 bu 8 ft	1.3-4.5(10)	machine		Mech. Hydr.	95 bu 135 bu	1635- 1955-	215- 235-	70 80	
Fertilizer distrib. 6/	0.2-0.4	14	2-6(10)	machine & field		Mech.	1	50 to 70		w + 20	
Grain drill	0.25-0.40	20	3-6.5(7)	function &machine	30 - 80		1	135to160			
Corn & beet planter		20	2-5(7)	machine	25 - 40		1	90 to125			
Do. precision			-3	machine							
Potato planter	0.10-0.15	8to13	2 - 5	function &machine							
Transplanter			0.3-1.2(2)	hand feeding							
Broadseeder											

1/ Ref. 11), 14).

2/ Ref. 1), 9).

3/ Ref. 1), 14), 22), 7), 29), 13). Figures from ref. 13) given in ()

4/ Ref. 1), 2), 19) p. 186

5/ Ref. 1) p. 207, 9), 25), 26).

6/ Hopper capacity 1.7 - 2.1 cuft/ft width

7/ 8 - 20 hp/ft. Typical rotational speed 200 - 300 rpm. Ref. 1) p. 201.

8/ Ref. 1) p 33, 19) p 202.

TABLE 211. TECHNICAL REQUIREMENTS. OPERATIONS DURING THE GROWING SEASON.

Field efficiency: row cultivator 80 - 90 %. 7/

Implement	Capacity acres/hr&ft 1/	Present max.size ft 2/	Speed range mph 3/	Speed limited by	Pull pr ft width lbs 4/	Weight and dimensions 5/ Weight lbs/ft	Length inch	Width inch	Height inch
Row crop cultivator	0.15-0.25	14	1-5(7)	steering &function	35-130	135			
Spring tine weeder				function	25-35				
Rod weeder				function	80-110				
Thinner				steering &function					
Sprayer 6/		15 (80)	2-5(10)	steering & field					
Dusting equipment				field					

1/ Ref. 11), 14).

2/ Ref. 1) p 259, 484.

3/ Ref. 1), 7), 13), 14), 22), 29). Figures from ref. 13) given in ().

4/ Ref. 2).

5/ Ref. 1) p 259, 9).

6/ Typical rotational speed 100 - 200 rpm (plunger type) Tank capacity 3.5 - 15 gal/ft. Clearance 30 inch.

7/ Ref. 19) p 202.

TABLE 212. TECHNICAL REQUIREMENTS. HARVESTING OF GRASS, HAY AND SILAGE.

Field efficiency: 70 - 90 % 7/.

Implement or part of implement	Capacity 1/	Present maximum size 2/	Speed range mph 3/	Speed limited by	Power type	Power 4/	Typical rotational speed.rpm 5/	Size ft	Weight lbs	Length inch	Width inch	Height inch	
								Weight and dimensions 6/					
Cutting mower bar	0.3-0.35 acres/hr&ft	7 ft	1-6(8)	machine	mech hydr	0.35-0.75 hp/ft	800 - 1000 (2000)	7	580	20	138	26	
rotating disc		5(7) ft	1-5(8)	machine	mech		500 - 1000						
Conditioner crusher		7 ft	-12	machine	mech			7	1460 to 1920	68- to 102-	105 to 95	40	
tedder			2 - 4	function &machine	mech								
Pick up				function &machine	mech								
Rake		8.3 ft	2-6(8)	function &machine	mech			8.3	880	130	124	58	
Baler	8 - 15 tons/hr		1-5(6)	machine	mech	8/		4.3 5	2750-5780--				
										132	30	34	9/
Chopper (field harv.)	50 - 75 tons/hr	8 ft 1-2 row corn	1-4.5(5)	machine &power	mech	10/	11/	5	1600 to 2000	144-	106	60 (108)	12/
								5	2500 to 4500--	230-	101		13/
Cut-loader			1.3-4.5	function &machine	mech hydr								
Dryer													

1/ Ref. 1) p 341, 362. 11), 14).

2/ Ref. 1) p 209, 26).

3/ Ref. 1), 7), 13), 22), 29). Figures from ref. 13) given in ().

4/ Ref. 1) p 341, 356-360, 9), 26).

5/ Ref. 1).

6/ Ref. 9), 26).

7/ Ref. 1) p 25, 19) p 203.

8/ Power: feeding 2 - 3 hp, pressing 6 - 10 hp at 3600 - 11000 lbs/hr. Aux. engine 16 hp for 10 tons/hr, 36 hp for 15 tons/hr.

9/ For press part.

10/ Power: feeding 1 - 3 hp. chopping 3 + (0.6 to 1.8)(Q tons/hr) hp for flywheel type. Aux. engines 30 - 40 (sometimes 75) hp.

11/ Flywheel speed 4500 fpm.

12/ Flail type.

13/ Cylinder and flywheel type.

TABLE 213. TECHNICAL REQUIREMENTS. GRAIN HARVEST.

Field efficiency: 55 - 75 % 5/.

Implement or part of implement	Capacity acres/hr/ft 1/	Present maximum size	Speed range mph 2/	Speed limited by	Power 3/ hp/ft	Typical rotational speed, rpm 3/	Weight and dimensions 4/ Size ft	Weight lbs	Length inch	Width inch	Height inch
Small grain harvest											
Cutter head	0.25-0.30	18 ft	1-4.5(6)	function &machine		400 - 450	1		40	w + 10	33+reel
Windrower		16 ft	3-	function &machine			10 16	2800- 3400-		w+13	
Pick-up device				function &machine							
Combine	0.22	18 ft	1-4.5(6)		1.5 pull 4 s.p.						
threshing				cleaning		200 -1500	7 10 12 16		32 36 36 36	39 46 51 54	30 34 34 34
separating				machine		200 - 250	7 10 12 16		114 134 139 143	39 46 51 54	28 28 28 28
cleaning				machine							
Grain storing (tank)											
Grain loading				machine							
Grain drying				function &machine							
Straw chopping (integral)				machine							
Straw baling (integral)				machine							
Grain corn harvest											
Picker	0.18-0.21	4 row	1-3.5(6)	function	0.6-1.5	500-600	2-row	3370		100	120
Husker				picker		250-700					
Sheller				picker		1700			90		62
Cleaning shoe				picker							
Stalk shredder			2 - 3	machine							

1/ Ref. 11), 14).

2/ Ref. 1), 7), 22), 29), 13).
Figures from ref. 13) are given in ().

3/ Ref. 1) p 388, 399.

4/ Ref. 9), 26).

5/ Ref. 1) p 25, 19) p 203.

TABLE 214. TECHNICAL REQUIREMENTS. ROOT HARVEST.

Part of implement	Capacity acres/hr&ft	Present max. size ft	Speed range mph. 1)	Speed limited by
Potato harvest				
Digger		2 row	1-3	separator
Separator			1-3	machine & function
Hopper				
Loading from machine				separator
Loading from ground				machine & function
Grader, washer				
Sugar beet harvest				
Top cutter			2-3.5	machine, function & driver
Top hopper				
Beet lifter			2.5-3.5	function & driver
Beet cleaner			1-3.5	machine
Beet hopper				
Sampling device				

1) Ref. 1) p 453, 7), 22), 29).

TABLE 215. TECHNICAL REQUIREMENTS. TRANSPORTATION AND LOADING.

Implement	Capacity lbs	Capacity sqft	Capacity cuft	Speed range mph 1/	Speed limited by	Weight and dimensions 2/ Size lbs	Weight lbs	Length inch	Width inch	Height inch
Truck				- 50	machine					
4-wheel wagon	-20000			0 - 20					< 96	Floor < 30 in. above ground
2-wheel wagon	-15000			Hand loading: 0.3 - 0.6	loaders	7000 to 14000		Wheel base: 82 to 114	Tread: 56 or 66	
2-wheel, driven wagon	-15000			In the field: 2 - 6	field & machine					
				Field roads: 2 - 10	field & machine					
				Highway: 5 - 20	machine & power					
Platform on power unit	-1000			0 - 20						
Front loader	2000	10	15	1-5(8)		1000 2000		(30) (35)	37 42	(23) (23)
Elevator										

1/ Ref. 13), 22). Figures from ref. 13) given in ().

2/ Ref. 9), 26).

SECTION III. THE PARTS OF A POWER UNIT.

We have in preceeding sections considered the different operations we want performed on a farm, and we are now going to try to find a suitable power unit or units for these operations. Suitable means primarily that the power unit shall fulfill the requirements of the operations, but also of equal importance is that it shall be technically efficient. Technical efficiency may be measured by e.g. the amount of work a power unit of given size can perform and at what cost the operation is performed.

The amount of work done as well as the cost of operation, is determined by how efficiently the power from the engine is transformed into useful work. For power transmissions through rotating shafts the transmission efficiency is fairly high, but when the power is delivered in form of pull, it can be very low. In order to determine the suitability of different power units we therefore must study their drive efficiency or effectiveness. This will be done in Chapter 8.
Related to the drive effectiveness is the steering effectiveness, which will be discussed in Chapter 10.

All parts of a power unit have an influence on how good it is. The influence of the design of individual parts themselves on the overall efficiency will not be discussed here, but only the effect of different layouts, i.e. of how the parts are arranged relative to each other and relative to the implements. Consideration must, of course, be given to the special requirements on position which the power unit parts might have. These requirements are therefore described in the first part of this section.

A further and important limitation of the ways to arrange the implement and the parts in the power unit is that the combination must have enough stability under all but not too abnormal conditions. Chapter 9 describes how the stability is influenced by the layout.

Chapter 7. The Functional Requirements of the Parts of the Power Unit

As the name implies, the power unit contains the source of power for the implement whether the power be delivered as pull, power in a rotating shaft, oil under pressure, etc. The power unit is always considered automotive and also carries the implement when this has no means of support. Thirdly, the implement is maneuvered from the power unit, the driver's platform generally being a part of the power unit.

The elements of a power unit are engine (engines), transmission, driving wheel (wheels), steering wheel (wheels), driver's platform with controls for the power unit and the implement, and means for connecting the implement to the power unit. All this is built into a suitable frame. From some of these elements there usually are power outlets to the implements for rotational, hydraulic, pneumatic or electric energy. Steering wheels might be driving wheels also. Tracks might be used instead of wheels, and other substitutes for wheels might also be seen.

The Engine

The type of engine is not of major importance for the general layout of the power unit, but I will assume that it is some sort of internal combustion engine. There might be more than one. For the internal combustion engine the most important accessories from the layout point of view are the air intake and the air cleaner, the exhaust pipe and the spark arrester, the fuel tank, the battery, and the engine-cooling elements. The remaining parts can be placed on or in the motor block and considered a part of the engine unit.

The engine can function as well lengthwise as crosswise in the vehicle and as well horizontally as vertically. No special consideration need therefore be given from the engine's own standpoint how it is placed in the vehicle. The main viewpoints are in what direction the main power outlet is, available space, the influence of the engine weight on the vehicle and how to service the engine. These are the only considerations given the engine in the further discussion.

The Transmission

The transmission transmits the power to the driving wheels. Its purpose is (1) to give the power unit the desired speed, and (2) at the same time allow the engine to run at a speed where it can deliver the power needed in the most efficient way.

There are today mechanical transmissions,in some cases in connection with hydrodynamic parts, hydrostatic transmissions and electric transmissions. The evolution is making rapid progress in this field.

The transmission plays an important role in tractor layout because it limits the possibilities to arrange the drive. Some new transmissions, e.g. hydrostatic and electric, permit more freedom in this aspect, but have other disadvantages. The technical possibility to get the drive to the wheels and the space needed for the transmission are the only concern that will be given the transmission in this study. A few cases where the transmission is used for steering will also be mentioned.

Different _wheel_ _arrangements_ will be discussed in Chapter 11.

Connecting Power Unit and Implement

There are three principally different ways to connect power unit and implement. A _pulled_ _implement_ (trailing implement) is fully carried by its wheels, etc. and is coupled to a hitch point in the tractor rear end. The weight of a _semi-mounted_ _implement_ is partially carried by the power unit and partially by the wheels of the implement. A semi-mounted implement can be placed on any side of the power unit, not only behind it. A _mounted_ _implement_ is at least in transport carried entirely by the power unit. When working it may run entirely or partly on its own wheels, working surfaces, shoes, etc. A mounted implement may be placed in any position relative to the power unit and is accordingly called rear-mounted, mid-mounted or front-mounted. Front and rear-mounted implements are often centrally mounted, but mid-mounted implements might be centrally mounted or side-mounted.

As a general rule the following demands on the mounting system ought to be satisfied:

1. One man must be able to attach the implement without help and with normal physical effort. It must be born in mind that on all sizes of farms, the power unit and its implements are a one-man tool.

2. The time needed for mounting must be in a reasonable proportion to the effective working time of the implement. The time needed for mounting and dismounting is a waste time during which no productive work is performed. If the productive working time is short compared to the time for mounting, the average efficiency will be low and in some cases so low that the use of a tractor implement does not give any gain compared to doing the work by hand. Short working periods appear on farms of all sizes, but to the greatest extent on the small farm where the same tractor has to be used for many tasks often on the same day. A short mounting time is therefore especially important for such tractors. On larger farms it is not of the same importance because the tractor is used for a longer time in the same work. Furthermore, larger farms often have more than one power unit and can afford to designate one of them for certain work, where the implement consequently might be mounted for a long time uninterruptedly. It is in some cases possible to have a power unit always designated to one implement only and thereby, in fact, to create a self-propelled implement. This procedure may, in some cases, be justified but cannot for economical reasons be applied for most implements.

3. The attachment should preferably be made without loose bolts, pins, etc. and, if possible, also without tools such as wrenches, screwdrivers, etc. Such small parts are apt to disappear or be damaged in the field.

4. If possible, the same system for attachment should be used for all implements that are supposed to go with the power unit. This standardization of the mounting system will become an increasingly difficult problem as better types of mounting for individual implements are designed. Individual perfection and generality can very seldom be achieved at the same time. The problem will be less difficult if the number of implements for each power unit is reduced.

5. The easiest exchange of implements is made possible if all individual adjustments on the implements are performed inside the implement and not on the power unit, i.e. if the hitch points are fixed on the tractor (ref. 17). Then all implements would be ready to work immediately, being adjusted in the same way as they were last time they were used. This system, however, necessitates some duplication of adjustment devices and is therefore slightly more expensive.

Mounting of the implements has a decided influence on the drive effectiveness of the power unit because the weight of the implement and eventual downward pull exerted on it can be used to increase the load on the driving wheels of the tractor and thereby its pulling ability. This is the natural way to increase the drawbar pull and should be used before other methods. This influence of mounting will be thoroughly discussed in Chapter 8. Furthermore, mounting makes it easier to maneuver the implement and to transmit power to it. The implement design becomes simpler and the implement thus cheaper. Therefore, the implement should be mounted on the tractor whenever this is possible.

Mounting also has a decided effect on the steering effectiveness, and the stability of the combination, as will be discussed in Chapters 9 and 10.

Some implements require to be mounted in a certain position within the combination implement-power unit. This is indicated in Tables 201 - 206.

A brief summary of the characteristics of different ways of mounting and hitching may be given thus:

If a mounted implement, requiring a large pulling force, is rear-mounted the result is an advantageous transfer of load to the rear wheels, even if there is a risk that the transfér becomes too large, causing poor steering and overturning of the tractor. The implement tends to keep the tractor on a straight course. It is easily mounted. The wheeltracks of the tractor can easily be erased.

Light implements can be side or front-mounted. In these positions the implements are easy to watch and easy to mount, at least if the power unit is suitably designed for it. Front-mounted implements can open a road into a field. With a front or side-mounted implement another implement can be rear-mounted making two or more simultaneous operations possible.

Some implements are favorably mounted between the front and rear axles. There they are easy to watch and to steer and they put an even load on both front and rear wheels. They might, however, be difficult to mount in this position.

Heavy and bulky implements ought to be made semi-mounted, i.e. some of their weight ought to be carried by their own wheels. How rigid the connection between tractor and implement shall be made, is determined by how often the implement must be disconnected and how complicated the power transmission to the implement and the maneuvering of it is. Semi-mounting increases the drive effectiveness of the tractor and makes the aggregate easier to handle, compared to pure trailing implements.

Pulled (trailing) implements can be very easily connected to the tractor and disconnected from it. They can be moved without a tractor which can be an advantage for e.g. a wagon. This reason is especially important for implements that are used together with the tractor only for a short time on every occasion.

The Driver and The Driver's Platform (Cab)

It is possible that in the future no driver will be needed on the power unit, the unit being governed and steered by a mechanical device, following a predetermined program. It will, however, take a long time before this can be common practice and up till then a driver will be needed.

When there has to be a driver watching the power unit and its attached implements, there seems to be very little to be gained by using such remote control where the driver is placed at some fixed point in the field and controls the power unit by telecommunication. He then gets a poorer view of what happens around the implement and less control of the different factors. Demonstrations of radio-controlled tractors are therefore more a way of arousing public interest than of general practical value. In the case, however, where implement and power unit are far apart, as e.g. in winch-hauling of timber, radio control might be useful.

In order to utilize the driver's time more efficiently, it might sometimes be desirable to hitch two or more operational units together and to govern them all by a driver on one of them. This type of remote control seems a more profitable and practical prospect than radio control. The system is in wide use on e.g. railroads and has also been tried in agriculture in the form of tandem tractors or in prior days, when large teams of horses or mules were used.

The power unit and the implements ought to be handled by the same man as far as possible. When the horse was the power unit, the driver usually walked behind both horse and implement and could therefore both rein the horse and watch the implement, both of them being in his field of view. When the tractor was substituted for the horse, the driver moved to the tractor where he was placed in front of the implement and often far away from it. This made it sometimes necessary to use another man on the implement. This could for some time be justified because the output per man hour was still increased by the increased speed and working width of the tractor drawn implement. On a small farm, however, with just one or two workers, it is often difficult to get two men for one operation and the mechanization could therefore not proceed very far, until both the tractor and the implement could be managed by one man. Even on a larger farm a one-man unit is usually desirable.

It is, however, not enough that the tractor and the implement can be driven by a single operator. It is also essential that they can be driven with as little stress and fatigue on the driver as possible. If the driving is in any way inconvenient, this will result in a lower accuracy, a lower speed and more pauses for rest and "repair".

The following conditions ought to be fulfilled in order to give a convenient driving of the power unit:

1. The driver and the implement ought to be placed in the right position to each other. This means that all parts where something happens can be seen from the driver's position. It is further important that parts that need a continuous supervision are inside the driver's normal field of view, i.e., in a certain direction and at a certain distance from him. This is especially important e.g. for row cultivators. An investigation by NIAE (ref. 24) shows that such vital parts should not be more than 40° off the direction of travel and not less than 6 feet from the driver's eyes. Another investigation shows that even a single beam in the line of sight is very disturbing (ref. 22). Further investigations are needed in this field, however. Not all implements need such continuous supervision and can therefore be placed away from this ideal position, but the condition of visibility must always be considered. The requirements on supervision are indicated in Tables 201 - 206.

2. Servopower ought to be used for all heavy adjustments of the implement. Most common is at present the hydraulically actuated three-point hitch which can be used for all implements mounted there. The free hydraulic cylinder (remote control cylinder) gives a greater freedom in applying the hydraulic power. Electric and vacuum servopower can sometimes be used, e.g. for applying the brakes on a trailer. The servopower ought always to be available, or at least as soon as the engine runs. The servopower for lifting and adjusting implements could in some cases be automatically released. This is further discussed below. Examples of prospective cases are given in Tables 201 - 206.

3. The driving is made easier if the implement is to some extent self-steering, i.e. if it tends to return by itself to the wanted position when it has deviated from it. Otherwise all deviations, even small ones, have to be counteracted by the driver.

In many field operations the operational unit is driven along a furrow, row, swath, etc., made in a preceeding cycle. In such cases the steering could easily be made automatic. The driver could thereby be released from continuous steering and watching direction and could devote more time to watch the operation of the implements. He would probably occasionally have to watch the automatic steering also, but this would be much easier than to do the actual steering. In a few cases where very high accuracy in steering is needed, he might have to do additional fine steering.

Another group of functions which could be automized are the operations at the headland, e.g. raising and lowering the implement and shutting it off and on. If the responsibility for these functions could be taken away from the driver he could devote all his attention to steering the unit and would probably not drive into the ditch as often happens now.

4. An important part of a convenient driving is an easy way of transporting power unit and implement to and from the field.

5. The points given above refer to the influence of the implements on the driver's position and on the ways of maneuvering the power unit. The driver himself must also be given due consideration. This means e.g. that all controls should be conveniently located relative to the driver, that they should move in the best direction, and that they require the least physical effort from the driver. These points have been studied by e.g. Dupuis (ref. 12). From the driver's platform can furthermore be required that it shall protect the driver from dirt, vibrations, rain, heat, cold, gases, etc. It must be easy for the driver to get on and off the platform. If possible, it shall protect the driver from severe injury, if the power unit overturns.

The point, which must be especially taken care of, when making the layout of the power unit, is the first one about supervision of the implement. The fifth point will be considered by assuming that the power unit will be equipped with a cab containing all necessary controls neatly arranged. The other points enter the problem mainly at a later stage than the layout stage.

The Power Take-Off

The mechanical power take-off in the form of a shaft or a belt is the most efficient. It can, however, not be used in more than a few directions from the tractor body. It is also often difficult to connect it to implements that move relative to the power unit.

Hydraulic power take-off in form of oil under pressure is now used for certain functions, e.g. power cylinders for loaders, etc. Hydraulic power take-off could, however, also be used for faster, rotating or reciprocating parts. Experiments with hydraulically driven cutter bars have been made in several places. Hydraulic power transmission has the advantage of greater flexibility and can be carried to any point around the power unit.

Electric power take-off seems still to be too expensive for most purposes. It is characterized by great flexibility and easy control.

The method for power transmission must be given some consideration when deciding where to place an implement in the operational unit, and it might exclude some otherwise good possibility.

CHAPTER 8. The Drive Effectiveness of a Power Unit

The drive effectiveness is intended to give a measure of how effectively the torque from the engine is transformed into useful pull at the implement. (The word effectiveness is used instead of efficiency because the word efficiency has often been given the specific meaning of ratio between output and input energy, i.e. not forces and torques as in this case.)

As a first step we need to define "useful pull". Take as an example the moldboard plow. The useful forces in a restricted sense are the forces which break the soil apart and turn it. To this is added unproductive forces to overcome friction, made necessary by the working principle itself; e.g., the friction between the soil and the moldboard. These two types of forces cannot be changed without changing the basic working principles of the implement.

Then there is resistance caused by the devices which take the reaction forces from the implement. Examples are friction against the landside of the plow bottom and rolling resistance of the plow wheels. These forces can be influenced by proper mounting of the implement where the reaction forces are taken by wheels instead of by sliding surfaces and by large wheels instead of small wheels. Sometimes the reaction forces can be used to increase the drive effectiveness as for instance when the weight of the implement is used to put load on the driving wheels of the power unit. In general these resistance forces, caused by supporting devices, will also be included in what we call useful pull from the power unit. For some mounted implements it will, however, not always be possible to completely distinguish them from interior forces in the power unit, and an explanation about these forces must therefore be given for each individual case.

Of course, the rolling resistance of the power unit itself should not be considered useful, even if it is unavoidable (for automotive units). Nor should the force caused by gravity on the power unit on a slope be counted as useful.

Useful pull could therefore be defined as the horizontal force delivered by the power unit in order to overcome working forces on the implement and resistances to its motion.

The word effectiveness implies a comparison between what we really get, in this case useful pull, and what we should have obtained under most effective arrangements. What, then, determines this maximum?

The pull is limited mainly by two factors; the torque available at the drive wheels and the slip in the wheel-ground contact. If the pull is exerted above a certain height above the ground, the stability of the power unit may also become critical.

From operational reasons most tractors have a low gear which gives a much higher torque in the drivewheels than the other limits will permit. Torque is therefore very seldom a limiting factor for the pull if not a certain speed is also required. This limit is also easily increased by using a larger engine.

The stability limit for the pull will be discussed in connection with overall stability in Chapter 9. There usually is no difficulty to stay within the stability limit if one is aware of the risk in exceeding it.

The slip limit remains the most serious limit. As explained in Appendix A, the maximum net tractive effort of a wheel is expressed as

$$F_2 = f_{opt}F_1$$

where F_1 is the vertical load on the wheel and f_{opt} is a coefficient determined by the soil, by how much slip we can allow and by many other less important factors.

We therefore can write:

Drive effectiveness =

$$= \frac{\text{useful pull}}{\text{maximum value of } (f_{opt}F_1)} = \frac{\text{useful pull}}{f_{opt}(F_1)max} \times \frac{f_{opt}}{(f_{opt})max} =$$

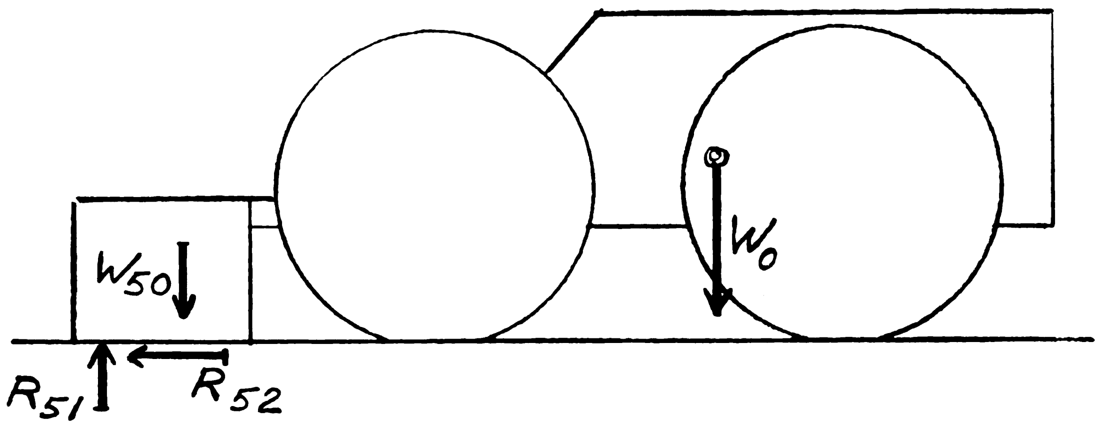
= drivewheel loading effectiveness x ground grip effectiveness

<u>Drivewheel Loading Effectiveness</u>

For the following study of the mechanics of the power unit a system of coordinates, forces and notations has been used, which is thoroughly explained in Appendix B. Here shall only be pointed out, that all dimensions are given as dimensionless quantities, in fact as ratios between the actual dimension and the wheelbase. In other words, they apply for a power unit with the wheelbase equal to 1 length unit.

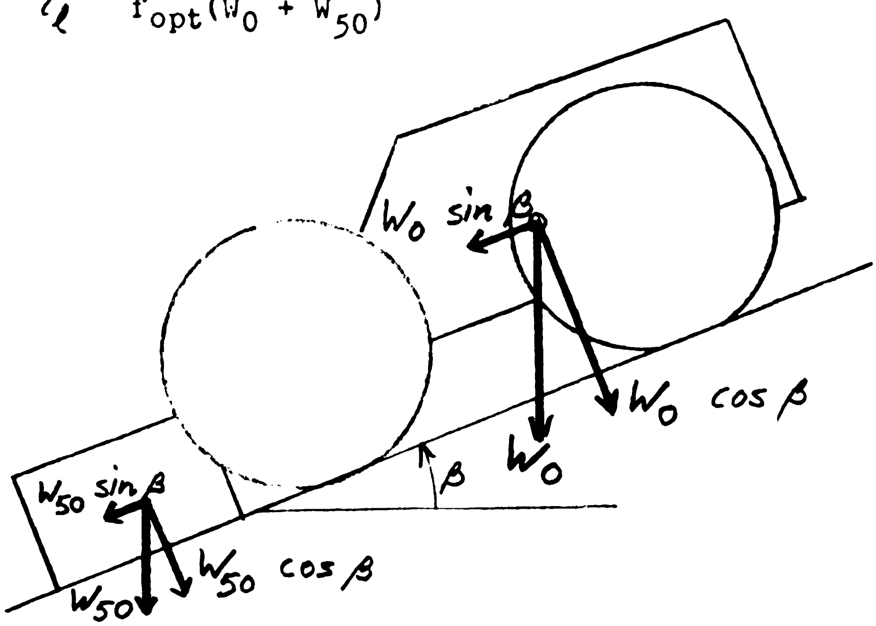
Excluding the rare occasion, when the usable reaction force R_{51} from the soil on the implement is directed downwards (negative) the maximum available load on level ground is the sum of all weights, $W_0 + W_{50}$. The maximum net tractive force is then

$$f_{opt} (W_0 + W_{50})$$



The tractive force is utilized as the force by which the implement works on the soil, which has the same magnitude as the reaction force R_{52}. This is our useful pull. If R_{52} is determined for $f = f_{opt}$, the drivewheel loading effectiveness η_ℓ given below indicates how effectively the available weight is distributed on the drivewheels in order to produc traction.

$$\eta_\ell = \frac{R_{52}}{f_{opt}(W_0 + W_{50})} \qquad (30a)$$



On a slope the available load, perpendicular to the ground, is only $(W_0 + W_{50})\cos\beta$. Useful work is produced also in moving the implement up or down the slope which requires the force $W_{50}\sin\beta$. η_ℓ might be defined as

$$\eta_\ell = \frac{R_{52} + W_{50}\sin\beta}{f_{opt}(W_0 + W_{50})\cos\beta} \tag{30b}$$

Level Ground

Using the basic equations B3-5a, 6, 7 and 8 in Appendix B, we get for a power unit on horizontal ground:

$$R_{52} = W_0 \frac{1}{x_{11} - x_{21} - y_{52}(f_2 - f_1)} \cdot$$

$$\left[(f_2 - f_1)(-x_0 - i\,x_{50} + \ell\, i\,x_{51}) + (1 + i - \ell\, i)(f_2 x_{11} - f_1 x_{21})\right]$$

$$\eta_\ell = \frac{1}{1+i} \cdot \frac{1}{f_{opt}} \cdot \frac{1}{x_{11} - x_{21} - y_{52}(f_2 - f_1)} \cdot$$
$$\left[(f_2 - f_1)(-x_0 - i\,x_{50} + \ell\, i\,x_{51}) + \right.$$
$$\left. + (1 + i - \ell\, i)(f_2 x_{11} - f_1 x_{21})\right] \tag{31a}$$

where i indicates the ratio of implement weight to power unit weight and ℓ indicates how much of the implement weight is carried by its own wheels, etc.

This is the shortest, complete expression for η_ℓ, but the parenthesis can also be written as

$$-(f_2 - f_1)\left[(x_0 - x_{21}) + i(x_{50} - x_{21}) - \right.$$
$$\left. - \ell\, i(x_{51} - x_{21})\right] + f_2(1 + i - \ell\, i)(x_{11} - x_{21})$$

which shows, as expected, that if the rear point of suspension ($x = x_{21}$) had been chosen as origin, the equations would have become much simpler. However, x_{21} is not constant, wherefore this point is not well suited as a reference point.

For an all-wheel driven power unit we can in the ideal case assume $f_1 = f_2 = f_{opt}$ which gives

$$\eta_\ell = \frac{1 + i - i\ell}{1 + i} = 1 - \frac{i\ell}{1 + i} \qquad (31b)$$

This shows, that the drivewheel loading effectiveness of such a unit depends only on the magnitude of ℓ, i.e. to what extent the implement is self-supporting. An all-wheel driven power unit must consequently use fully mounted implements to achieve a drivewheel loading effectiveness equal to 1.

Making the approximation, that $x_{11} - x_{21}$ is equal to the wheelbase = 1, we get for all types of power units:

$$\eta_\ell = \frac{\frac{f_2 - f_1}{f_{opt}}}{(1 + i) \;\; 1 - y_{52}(f_2 - f_1)} \cdot \left[- x_0 - i x_{50} + \ell i \, x_{51} + (1 + i - \ell i)\left(\frac{f_2}{f_2 - f_1} + x_{21}\right)\right] \qquad (31c)$$

On a Slope

The basic equations in this case are given in Appendix B as equations B 3-5b. With $\eta_{\ell \, slope}$ defined as

$$\eta_{\ell_{slope}} = \frac{R_{52} + W_{50} \sin \beta}{f_{opt}(W_0 + W_{50}) \cos \beta}$$

and using the approximation $\ell / \cos \beta = \ell$, we get

$$\eta_{\ell \, slope} = \eta_{\ell \, level} + \frac{1}{1 + i} \frac{\tan \beta}{f_{opt}} + \frac{1}{1 + i} \cdot \frac{(y_0 + i \, y_{50}) \tan \beta}{x_{11} - x_{21} - y_{52}(f_2 - f_1)} \cdot \frac{}{f_{opt}} \qquad (32)$$

This expression gives the change of the drivewheel loading effectiveness, caused by the slope. The equation shows that the slope causes the same change in effectiveness whether the implement is mounted or not, as ℓ does not enter the expression.

Equations 31 and 32 are very clumsy to handle analytically but could favorably be set up on an analog computer which would make it easy to study the influence of changes in all the different factors and to find the best combination of them.

Another use for the drivewheel loading effectiveness may also be mentioned. Equation 30a can be written:

$$W_0 = \frac{R_{52}}{f_{opt} \cdot \eta_\ell} - W_{50} \qquad (33a)$$

and

$$W_0 = \frac{R_{52} + W_{50} \sin \beta}{f_{opt} \; \eta_\ell \; \cos \beta} - W_{50} \qquad (33b)$$

For a given implement R_{52} and W_{50} are known, as well as the condition of the field where it works, i.e. f_{opt}. It is then possible to approximately calculate the absolute minimum weight of the power unit (for $\eta_\ell = 1$) or the minimum weight for any other η_ℓ-value, chosen from experience.

<u>The Effect on the Drivewheel Loading Effectiveness of a Change From Rear-Wheel-Drive to Front-Wheel-Drive</u>

For rear-wheel drive, f_2 is positive and f_1 is negative and usually numerically smaller than f_2. For front-wheel drive the opposite is true. Therefore $f_2 - f_1$ can be written $= \pm f_{opt}(1 + n) = \pm k_1$ where $0 < n < 1$ and the plus-sign applies for rear-wheel drive and minus sign for front-wheel drive. If we substitute positive constants k for all factors, which are not influenced by this discussion and assume $x_{11} - x_{21} = 1$, we get

$$\eta_\ell = \frac{1}{1 \mp k_1 y_{52}} \Big[\mp k_2 \Big\{ (x_0 - 0.5) + i(x_{50} - 0.5) - i\ell(x_{51} - 0.5) \Big\} + (\pm k_3 x_{21}) + k_4 \Big] \qquad (31d)$$

where $k_2 = \frac{1 + n}{1 + i}$; $k_3 = \frac{1 + n}{1 + i}(1 + i - \ell i)$;

$$k_4 = \frac{1 - n}{2} \frac{1 + i - \ell i}{1 + i}$$

and the upper sign applies for rear-wheel drive.

This expression shows:

1. the effectiveness has one factor, k_4, independent of rear or front-wheel drive. The magnitude of this factor is close to but less than ½.

2. the rolling resistance, represented by x_{21}, decreases η_ℓ for a front-wheel drive, increases it for a rear-wheel drive.

3. If the center of gravity and the implements are placed at the same distance from the middle of the tractor in both cases, but in front of it on a front-wheel drive and behind it on a rear-wheel drive, there is no difference caused by the gravity.

4. Increasing the height of the pull, y_{52}, increases the effectiveness for a rear-wheel drive, decreases it for a front-wheel drive.

A study of the formula for η_ℓ on a slope shows that η_ℓ increases with increasing slope for rear-wheel drive and decreases for front-wheel drive.

Most of these reasons speak against front-wheel drive. In some cases, however, front-wheel drive can give better drive-wheel loading effectiveness than rear-wheel drive.

<u>The Stall Limit</u>

The stall limit is one of the limits for where an implement can be mounted on a power unit. When the implement is placed too far ahead on a rear-wheel driven unit or too far behind on a front-wheel driven unit, the load on the drive-wheels is no longer enough to give any useful force. (R_{52} + $+ W_{50} \sin \beta$), i.e. η_ℓ becomes = 0. At this point the unit is stalled. The condition $\eta_\ell = 0$ inserted in equation 31a for level ground gives the following limit for x_{50} and x_{51}.

$$x_{50} - \ell x_{51} = (1 - \ell + \frac{1}{i}) \frac{f_2 x_{11} - f_1 x_{21}}{f_2 - f_1} - \frac{x_0}{i} \quad (34a)$$

or if $x_{51} = x_{50}$ (i.e., the implement is supported under its center of gravity):

$$x_{50} = \left[1 + \frac{1}{i(1 - \lambda)}\right] \frac{f_2 x_{11} - f_1 x_{21}}{f_2 - f_1} - \frac{x_0}{i(1 - \lambda)} \qquad (34b)$$

Effect of Non-Symmetric Weight Distribution

Earlier equations for the drive-wheel loading effectiveness can be directly applied for all symmetrical cases; i.e., where the individual resultants of the forces lie in the center plane, the xy-plane.

If the drive-wheels are unequally loaded, the maximum pull is decreased by an amount determined by the inequality and by the differential (differentials).

To illustrate the effect on a two-wheel axle, we assume the wheel loads are

$$F_{1_h} = (1 + \Delta)\frac{F_1}{2} \quad \text{and} \quad F_{1_\ell} = (1 - \Delta)\frac{F_1}{2} \quad .$$

The differential gives the torque

$T_\ell = (1 - d)\,\frac{T}{2}$ to the wheel which slips most

and $T_h = (1 + d)\,\frac{T}{2}$ to the least slipping wheel.

Because we want to see the effect of uneven load only, we assume the same coefficients f_{opt} and f_{res} on both sides. In addition we use the equations

$$F_{2_\ell} = \frac{T_\ell}{y_0} - F_{1_\ell} f_{res} = F_{1_\ell} f_{opt} \;;$$

$$F_{2_h} = \frac{T_h}{y_0} - F_{2_h} f_{res} \;; \qquad F_2 = F_{2_\ell} + F_{2_h}$$

The pull F_2 from the axle can be calculated to

$$F_1 f_{opt}\left[\frac{1 - \Delta}{1 - d} - \frac{\Delta - d}{1 - d}\;\frac{f_{res}}{f_{opt}}\right] \quad \text{valid for } d \leq \Delta$$

which should be compared to the pull with even load which is $F_1 f_{opt}$. We therefore see that the effectiveness which we may call $\eta_{sideload}$ is

$$\eta_{sideload} = \frac{1 - \Delta}{1 - d} - \frac{\Delta - d}{1 - d} \frac{f_{res}}{f_{opt}} \qquad (35)$$

This is = 1 as long as d is = Δ (or greater).

For an ideal differential d = 0 and our effectiveness is $= 1 - \Delta - \Delta \frac{f_{res}}{f_{opt}}$.

This shows that both the diminished torque and the rolling resistance of the "unused" part of the load on the high-loaded wheel decrease our effectiveness.

Similarly the effect of uneven load on a four-wheel drive power unit can be calculated.

Ground Grip Effectiveness

The other possibility to increase the pull of a wheel is to increase the coefficient of net traction f_{opt}, which is defined

$$f_{opt} = \frac{F_{2\ opt}}{F_1}$$

There are numerous ways to increase f_{opt}. This study is limited to the influence of different power unit designs and, therefore, only the following subjects will be taken up for discussion as they are determining for the layout. These two factors are the maximum carrying and tractive load on the wheels of a farm power unit and the influence of the wheels on each other.

The Maximum Load on a Wheel

The equations for drive-wheel loading efficiency will give the same result if all the weight is put on two wheels as if the load is distributed on four or six wheels. This might in many cases be true, but when the load on a single wheel is increased, a state will soon be reached where an increase in load does not give a corresponding increase in net traction. For still higher loads the result might even be negative. The factor maximum load therefore deserves study.

The maximum load is mainly determined by the qualities of the soil and by how the load is applied to the soil. Unfortunately, not enough is yet known about the mechanical properties of the soil in contact with a wheel. Bekker (ref. 4) has assumed the following relationship between normal pressure, p, tangential stress, τ, and the sinkage, z.

$$p = \left(\frac{k_c}{b} + k_\varphi\right) z^n \qquad \tau = c + p \tan \phi$$

where b is the width of the carrying surface and k_φ, k_c, n, c and ϕ are soil constants. It has not yet been shown that these expressions are correct for agricultural soil but an attempt has been made in Appendix A to develop formulas for f_{opt} where the influence of the load W and other factors can be seen. One of the expressions is

$$f_{opt} = \tan\phi + \frac{c}{p} - \left(\frac{p}{k}\right)^{\frac{1}{n}} \frac{1}{\ell(n+1)} - \left(\frac{p}{k}\right)^{\frac{2}{n}} \frac{A_1}{p\ell} - \left(\frac{p}{k}\right)^{\frac{3}{n}} \frac{A_2}{b\ell}$$

where $p = \frac{W}{\ell b}$, W is the load on the wheel, ℓ and b length and width of contact area and A_1 and A_2 further soil constants.

This formula indicates that f_{opt} decreases as p increases. In the first place, p is determined by the size of the tire. The relationships can be written as $p = p_i + p_c$

$$W = A_3 D^{n_1} B^{n_2} (p_i + A_4)^{n_3}$$

where p_i is inflation pressure. B and D are tire dimensions and A_3, A_4, p_c, n_1, n_2, and n_3 are tire constants (at present unknown).

This gives us reason to expect higher f_{opt} for a given load if tire dimensions are increased and inflation correspondingly decreased. This has also been found to be true in many cases, even if not in all. There seems to be specially favorable values with less favorable values on both sides. These are sometimes, however, at so low inflation pressures that they cannot be used with regard to buckling of the sidewalls, slip on the rim, etc.

These relationships have been partly studied, especially for very special purposes such as off-the-road military vehicles, but they should also be studied for ordinary agricultural conditions and extended to extreme values in order to give an idea about where the real limits are.

The size of the tire cannot be increased indefinitely, both with regard to cost and design. The limit seems to lie around 13 or 14 inch wide tires for ordinary inflation pressures up to around 20 psi and at about 18 inch for slightly higher pressures. The limit for outer diameter seems to be around 65 inches.

There consequently is a limit for the pull that can be taken from one wheel. One tractor manufacturer reports that this limit seems to lie at around 50 hp per wheel, developed at 5 to 7 mph. The inflation pressure used in this case indicates, however, that the highest f_{opt} would certainly be found at much lower load for ordinary agricultural conditions.

An investigation in the practically highest output per wheel seems to be of great value.

When the limit for the output from existing drive wheels on a power unit is reached, there is no other way than to distribute the power to more wheels. The evolution in the tractor field seems to have reached this state now.

Another conclusion can also be drawn from this discussion. The most favorable f_{opt} is found for a given combination of tire, load and inflation. If the load is changed considerably without changing the inflation, a less favorable value should be expected. Because change of inflation is usually not easily done, great fluctuations in the wheel load can mean poorer performance. Here again more information is needed.

Influence of the Wheels on Each Other

As mentioned in Appendix A, the gross tractive force between the soil and the tire must be reduced by the rolling resistance in order to get the net traction. If this rolling resistance could be decreased, the net traction would become larger. Traction could also be increased if the shear properties of the soil were improved.

Both these improvements probably take place when a wheel runs in the track made by another wheel. Such improvement was obvious from Ford's test of a tandem tractor and has also been shown by Reed-Cooper-Reaves (ref. 27). Bekker (ref. 4) discussed the problem but has later mentioned that this discussion is perhaps not quite correct. More research is needed here also. Some of the questions are: What is the best relation between the front and the rear wheel with respect to load, dimensions, and slip?

As much seems already very probable that the wheels should run in the same track when possible.

Other Factors Influencing f_{opt}

A third possibility to increase f_{opt} should also be mentioned. In many operations there are field surfaces around the power unit which would give different f_{opt}. At plowing for instance, the bottom of the furrow would give a different and usually better value than the unplowed land. Consequently, the drive wheels should, as far as possible, be placed where the highest f_{opt} could be expected. Sometimes, however, soil compaction or other reasons might make such an arrangement objectionable.

CHAPTER 9. The Stability of the Power Unit

The requirements for good stability and for high drive effectiveness on a power unit very often work in opposite directions. The trend has, therefore, been to decrease the stability down to a limit which was considered safe, thereby increasing the drive effectiveness. Unfortunately, it has not been possible to predict the stability exactly enough, and accidents where the stability has not been enough have therefore occurred. The evolution towards lighter tractors with stronger engines as well as the introduction of some mounted implements has made the problem increasingly important.

When discussing stability it must first be said that it is practically impossible to make a power unit one hundred percent stable under all conditions. A limit must be chosen for how much should be required and other safety measures be introduced to reduce the damage when this limit on rare occasions is trespassed. As such an emergency device may be mentioned the protective cab.

There are at least two principally different ways to prevent stability accidents. One is to increase the stability of the power unit, and this is the way that will be mainly discussed here. The other way is to make it impossible for the power unit to get into situations where the stability would be endangered. Such a way is to limit the forces which are involved to safe values. In most cases the wheel slip limits the torque that can be absorbed by the drivewheels.

Many vehicles slide sidewise on a slope instead of tipping over. Unfortunately, this way to safety is a very unreliable one because situations may occur where, for instance, the wheels do not slip.

Stability accidents occur as a rule when the power unit is started or turns. They seldom occur when the power unit is in steady motion, with or without implement, even if a few such accidents are known also. The equations must therefore contain all acceleration and similar forces as do equations B3, 4, 5c in Appendix B.

Longitudinal Stability

In some cases it is possible to run a tractor with the front wheels above the ground, i.e. with $R_{11} = 0$, because the instability due to pull may at first decrease faster than the basic longitudinal stability. In such a case, however, steering cannot be performed in the ordinary way and it is furthermore a dangerous way of driving if no special hitching device has been used. This exceptional case is therefore considered unstable in this study.

Equation B5c solved for R_{11} gives:

$$R_{11}x_{11} = W_0x_0\cos\beta - W_0y_0\sin\beta + W_{50}x_{50}\cos\beta - W_{50}y_{50}\sin\beta - R_{51}x_{51} - R_{21}x_{21} - R_{52}y_{52} + W_1x_0 - W_2y_0 + W_{51}x_{50} - W_{52}y_{50} + T_0 + T_{10} + T_{20} + T_{50} \qquad (36a)$$

Because x_{11} and W_0 always are positive quantities, $\neq 0$, the condition for stability $R_{11} \geqslant 0$ can be written:

$$x_0\cos\beta - y_0 \sin\beta + i\, x_{50}\cos\beta - i\, y_{50}\sin\beta -$$
$$- \ell\, i\, x_{51} - \frac{R_{21}}{W_0}\, x_{21} - \frac{R_{52}}{W_0}\, y_{52} + x_0 \frac{a_1}{g} - y_0\frac{a_2}{g} +$$
$$+ i\, x_{50} \frac{a_{51}}{g} - i\, y_{50} \frac{a_{52}}{g} + \frac{T_0}{W_0} + \frac{T_{10}}{W_0} + \frac{T_{20}}{W_0} + \frac{T_{50}}{W_0}$$
$$\geq 0 \qquad (36b)$$

(Equations B7-10 were also used.)

I write this equation thus:

(static stability) $\geq$ (instability due to rolling resistance) + (instability due to pull) + (inertia instability).

In consequence with earlier work, the expressions above are partly dimensionless. If equation 36a is multiplied by L and equation 36b by W_0L, they would be expressed in foot-pounds. (L = wheelbase)

Static Stability

$$\text{Static stability} = x_0\cos\beta - y_0\sin\beta + i\, x_{50}\cos\beta - i\, y_{50}\sin\beta - \ell\, i\, x_{51} \qquad (37a)$$

Here should first be noted that x_{50} and x_{51} often are negative quantities and that consequently $x_0\cos\beta$ is the only quantity in this expression which is always positive. It is called static stability because for a static power unit equation 37a is all that remains of the stability equation 36b. The static stability does not change when the power unit starts moving, with exception for some eventual change in the ℓ-value.

The static stability could also be written:

$$(x_0 + i\, x_{50} - i\, \ell\, x_{51}) - \left[(1 - \cos\beta)\, (x_0 + i\, x_{50}) + \sin\beta\, (y_0 + i\, y_{50})\right] \qquad (37b)$$

where the first part is the static stability on level ground and the second part is the instability due to slope.

The static stability could be characterized by the angle β_s at which it is equal to zero.

$$\tan \beta_s = \frac{x_0 + i\, x_{50} - \frac{l_i}{\cos \beta_s} x_{51}}{y_0 + i\, y_{50}} \qquad (38)$$

This is an extension of the meaning of the angle of static longitudinal stability used by Worthington (ref. 31).

Instability Due to Rolling Resistance

The instability due to rolling resistance

$$= \frac{R_{21}}{W_0} x_{21} \qquad (39)$$

can take values up to the neighborhood of $(1 + i - l_i)\, x_{21}$. Even if x_{21} is relatively small, $1 + i - l_i$ is larger than any other factor in equation 36b and the importance of the instability due to rolling resistance is not negligible.

If not only stability but also weight transfer $(R_{11} \neq 0)$ is studied, regard must be given also to the rolling resistance of the front wheels $(x_{11} - 1)$.

According to our system of notations x_{21} for the rear wheels is the same as x_1 for a single wheel. This quantity is discussed in Appendix A. It seems as if x_1 should be relatively little influenced by the wheel diameter on a flat surface. Under exceptional circumstances, ditches, etc., where x_1 is relatively large, it is, however, also proportional to the wheel diameter as shown in Table A 2. In order to keep the instability due to exceptional rolling resistance constant, the ratio $\frac{\text{wheel diameter}}{\text{wheel base}}$ ought to be kept constant, provided the weight distribution between the axles is left unchanged.

Table A2 also shows that the pull F_2 has an influence on x_1. This will, however, be discussed in the next paragraph.

The neglecting of x_{21} (and x_{11}) seems to be one of the most important reasons for the discrepancy between calculated and measured values for weight transfer and longitudinal stability, which has been pointed out by Buchele and others.

Instability Due to Pull

The instability due to pull

$$= \frac{R_{52}}{W_0} y_{52} \qquad (40)$$

The maximum value of $\frac{R_{52}}{W_0}$ is in the neighborhood of

$$f_{opt} (1 + i - \lambda i)$$

This is usually less than 1.

The fact that the front end of a tractor became lighter and could rise when the tractor pulled has long been known and also that this happened earlier when the drawbar was high above the ground rather than low. There has, however, been a number of accidents where the tractor did not overturn until the load was disconnected which spoke against this concept of the effect of the pull on the stability, and the opinion has been expressed that the pull helped to keep the front end of the tractor down, as long as it was not applied above the center of the drivewheels.

The main explanation to the accidents seems to be that the pull has a considerable influence on the value of x_1. Take as an example a tractor which has dug down (Table A2). As long as the load $R_{52} = 0.6\ R_{21}$ is attached, the instability caused by the pull is 0.6 $y_{52} \frac{R_{21}}{W_0}$

or if we assume $y_{52} = \frac{D/4}{L} = 0.15$

the instability is $= 0.15 \frac{D}{L} \cdot \frac{R_{21}}{W_0}$

The instability due to rolling resistance is 0.1 $\frac{D/2}{L} \frac{R_{21}}{W_0}$

and the total instability from these two sources

$$= 0.20 \frac{D}{L} \frac{R_{21}}{W_0}$$

If the load is unhitched the first type of instability disappears, but the second increases making the total increase to

$$0.6 \frac{D/2}{L} \frac{R_{21}}{W_0} = 0.30 \frac{D}{L} \frac{R_{21}}{W_0}$$

i.e., an increase of fifty percent. Furthermore, the hitched implement had probably partly supported the tractor and this support was removed when the implement was unhitched.

Inertia Instability

The inertia instability =

$$-x_0 \frac{a_1}{g} + y_0 \frac{a_2}{g} - i\, x_{50} \frac{a_{51}}{g} + i\, y_{50} \frac{a_{52}}{g} - \left[\frac{T_0}{W_0} + \frac{T_{10}}{W_0} + \frac{T_{20}}{W_0} + \frac{T_{50}}{W_0}\right] \qquad (41a)$$

The following quantities are often negative (accelerating tractor assumed): T_{10}, T_{20}, a_{51} and x_{50}. For a rear-wheel driven tractor, T_{10} is usually small, especially when R_{11} is small as it is when the stability is low. a_1, a_{51}, T_0 and T_{50} are zero as long as the tractor is stable. A good approximation for most conditions is therefore:

$$\text{Inertia instability} = y_0 \frac{a_2}{g} + i\ y_{50} \frac{a_2}{g} - \frac{T_{20}}{W_0} \qquad (41b)$$

where T_{20} is negative.

It is seen here that all important inertia forces increase the instability of the power unit. Accelerations should therefore be kept low.

The inertia torque T can be written $T = \frac{I}{g}\alpha$. A relation between angular acceleration α and linear acceleration a can be found. It should again be pointed out that our force and length system is dimensionless. a must therefore be given in the same dimension as g and for $\frac{I}{W_0}$ must be used $\frac{I_{abs}}{W_0 L^2}$ which must be dimensionally correct (foot and pound, i.e., in both numerator and denominator).

Lateral Stability

Actually more accidents happen at present where the lateral stability has not been enough than where the longitudinal stability was insufficient. One of the most common accidents of this type is when one of the tractor wheels goes over the edge of a ditch along the field or the road; but accidents also occur when one wheel passes a hindrance or on a sideslope when a heavy load is lifted or carried high above the ground in a front-loader.

As was the case for longitudinal stability, inertia or dynamic forces should also be considered for the lateral stability. In order not to complicate the equations unnecessarily, the only inertia force that will be included is the centrifugal force. For the power unit, the centrifugal force acts through the center of gravity of the power unit. Its lateral component is called W_3 and has the magnitude $\frac{W_0}{g} z_\rho \omega^2$ where ω is the angular velocity of the c.g. and z_ρ is the z-coordinate for the center of rotation (same length dimension as g). Because it acts through the center of gravity in the same manner as the side component of the gravity on a slope, $W_0 \sin \gamma$, it can simply be added to $W_0 \sin\gamma$ in the equations and the resulting side force =

$$W_0 \left(\sin\gamma + z_\rho \frac{\omega^2}{g}\right) \qquad (42)$$

See further discussion in Appendix B.

We are first going to study the four-wheel tractor for which equations B12-18a, 19-21 apply, and we assume that the limiting device on the front axle movement is not brought into action. The condition for lateral stability can then be written:

$$R_{21_r} \geqslant 0;$$

We further assume a symmetrical power unit:

$$z_M = 0 \qquad z_{10} = 0 \qquad -z_{11_\ell} = z_{11_r} = z_{11}$$
$$-z_{21_\ell} = z_{21_r} = z_{21}$$

Then equation B18b can be written, also using B13a and B8:

$$\begin{aligned} 0 \leqslant 2 R_{21_r} z_{21} &= R_{21} z_{21} + y_M \Big[R_{13_\ell} + R_{13_r} - \\ &- W_{10}\left(\sin\gamma + z_\rho \frac{\omega^2}{g}\right)\Big] - W_{20}\left(\sin\gamma + z_\rho \frac{\omega^2}{g}\right) y_{20} \\ &- W_{50}\left[\sin\gamma + (z_\rho - z_{50}) \frac{\omega^2}{g}\right] y_{50} + W_{50}(\cos\gamma\, z_{50} - \ell\, z_{51}) + \\ &+ R_{53} y_{53} \end{aligned} \qquad (43)$$

We can here recognize three stabilizing factors: $R_{21} z_{21}$, $y_M \left[R_{13} + \ldots \frac{\omega^2}{g}\right]$ and $R_{53} y_{53}$ and three instability factors connected to the height of the c.g. of the power unit y_{20}, to the height of the implement y_{50}, and to the position of the implement sidewise z_{50} and z_{51}.

The Basic Lateral Stability

$$R_{21}z_{21} \qquad (44)$$

That the lateral stability increases with the tread, $2z_{21}$ is well known and needs no further comment. It should, however, be noted that the other factor here is R_{21}, i.e., the load on the rear axle. If the load on the rear axle is small compared to the overall weight, as can be the case with heavy front-mounted implements, the basic lateral stability is also small. R_{21} can be calculated from equations B3-5 which show the different means to influence R_{21}.

The Stability of Front End Suspension, y_M

The coefficient for y_M in

$$y_M\left[R_{13_\ell} + R_{13_r} - W_{10}(\sin\gamma + z_\rho\frac{\omega^2}{g})\right] \qquad (45)$$

is in fact the force in the z-direction at the joint. It is almost always positive and this is therefore a stabilizing moment. It increases when y_M increases, i.e., when the pivot between the front axle (front part) and the rest of the power unit is placed higher up. For a tricycle tractor, where we can consider $y_M = 0$, this stabilizing moment does not exist.

There is a limit, however, for how large y_M can be. If y_M is made too large, the front axle becomes unstable and the front right wheel leaves the ground. This value is:

$$y_M \leq \frac{R_{11}z_{11} - W_{10}\left(\sin\gamma + z_\rho \frac{\omega^2}{g}\right) y_{10}}{R_{13} - W_{10}\left(\sin\gamma + z_\rho \frac{\omega^2}{g}\right)} \qquad (46)$$

As R_{11} almost always is larger than R_{13}, this means that y_M could be equal to or slightly larger than z_{11}, i.e., half the front tread.

Side Pull Influence

The side pull R_{53} has a stabilizing moment $R_{53}y_{53}$. As y_{53} usually is small, this influence is small. Furthermore, R_{53} can be negative. This moment is included in the equation mainly to show its importance compared to other lateral forces.

R_{53} also usually increases R_{13} and therefore has another slight beneficial influence.

A special side pull is the wind force on the implement and its load, which according to Appendix B, p. B10, can amount to 5 lb/sq.ft. net area. Even if this is a small force, it can be applied high up. Because it should always be considered negative, its influence ought to be checked for, e.g., frontloaders with hay, cotton bins, etc.

Influence of the Height of the Center of Gravity of the Power Unit

The expression

$$W_{20}\left(\sin\gamma + z_\rho \frac{\omega^2}{g}\right) y_{20} \qquad (47)$$

shows that it is the weight of the rear part only (20) and the height of its c.g. that are involved in this instability. $W_{20}y_{20}$ is usually, however, not far from W_0y_0.

The consequence of the influence of this factor is, of course, that the center of gravity of the power unit should be kept low in order to give high lateral stability.

Influence of the Height of the Implement

The instability caused by the height of the center of gravity of the implement is of the same type as that connected to the power unit itself.

$$W_{50} \left[\sin\gamma + (z_{\rho} - z_{50}) \frac{\omega^2}{g} \right] y_{50} \qquad (48)$$

Even if W_{50} usually is smaller than W_{20}, y_{50} often can be much greater, as for example for a front-loader. This might therefore be a much more serious cause of instability than the height of the power unit itself.

Influence of Implement Position Sidewise

The moment $W_{50}\ (z_{50} \cos\gamma - \ell z_{51})$ should always be considered negative for a symmetrical power unit because tipping could occur to either side and all other factors are symmetrical. The instability caused by mounting an implement to one side is therefore:

$$\left| W_{50}\ (z_{50} \cos\gamma - \ell z_{51}) \right| \qquad (49)$$

The Angle of Lateral Stability

An angle γ_s could be found for which the lateral stability is = 0 if ω^2 is 0.

CHAPTER 10. Steering Effectiveness of an Agricultural Power Unit

It is commonly known that the agricultural tractor can have steering difficulties, especially on soft and uneven ground and with heavy, rear-mounted implements. These difficulties have promoted the introduction of steering brakes, an effective if not efficient or desirable solution.

Some unorthodox tractors, e.g. the Unitractor, have encountered still greater steering difficulties than the ordinary tractors. It seems necessary to calculate and predict the steering properties of the tractor, which could otherwise seriously reduce its usefulness.

,The basic elements in the steering are the steering forces between the wheel and the soil. These are discussed in Appendix A.

What Causes a Vehicle to Turn?

Except for the purely theoretical case that there is no resistance at all to the movement, the turning of a vehicle must be propagated by a moment on the vehicle working around a vertical axis. This means that the steering force, caused by one wheel at an angle to its direction of motion, is not enough, but there must also be another steering force at another element of the vehicle and these forces must constitute a couple. This means that the steering effectiveness can be increased both by increasing the steering forces and by increasing the distance between them.

Steering Systems

There are two different ways to initiate a turn, namely to put some wheels at an angle to the original direction of travel and to introduce a difference in speed between the driving members. In the first case, the wheels can be turned individually around their center, automobile steering, or pairwise together with their common axle, pivot steering. Steering with different speed on the drive wheels might be called brake steering, even if this notation is in some cases misleading. ("Differential steering" would have been better.) These systems are exemplified in Table 301.

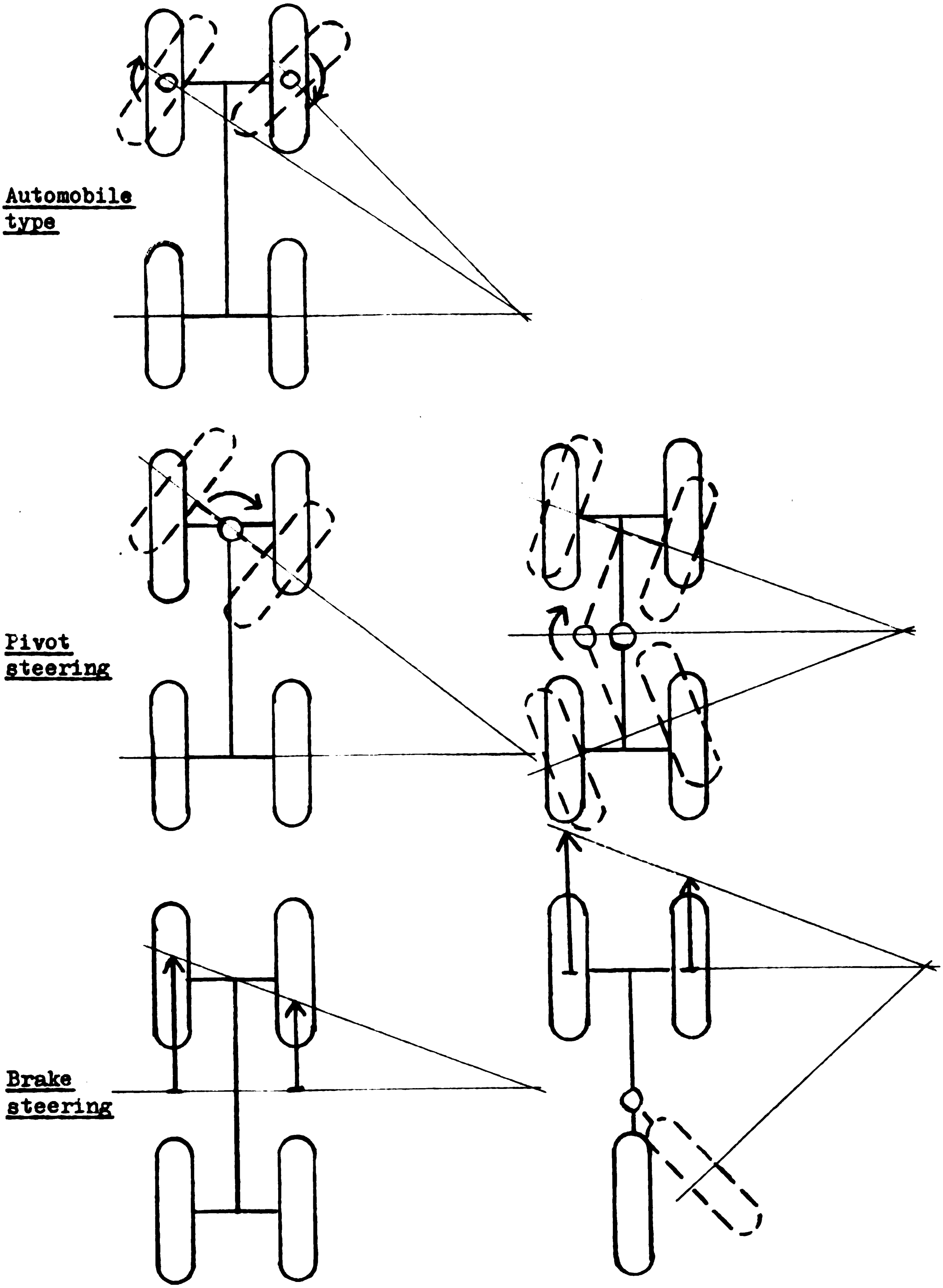
Automobile steering is controlled by a torque around the king pins. Brake steering is maneuvered via the transmission. Pivot steering is usually performed through a torque around the joint. Both automobile and pivot steering can be assisted by brake steering. Pivot steering should probably be given more attention than it has had up till now.

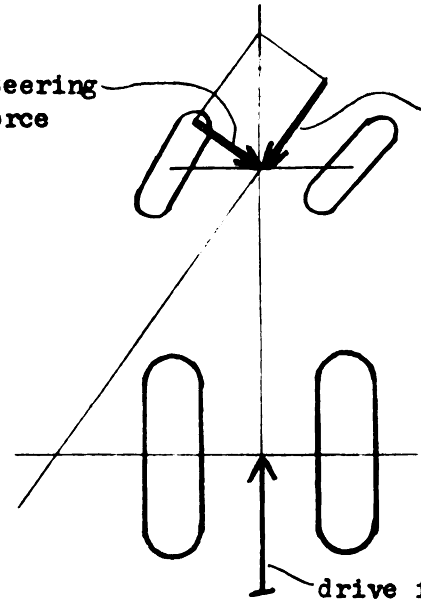
What Opposes Turning?

The need for a steering moment arises from the existence of forces and moments, which oppose the turning of the vehicle or which try to make the vehicle turn in an undesired direction. Some of the opposing forces are as follows:

1. The rolling resistance of steered wheels give a resultant which does not pass through the point of action of the resultant of the forces on the drivewheels. A steering force must therefore be introduced.

TABLE 301. BASIC TYPES OF STEERING.





2. When a wheel is forced to roll in a circle, there arises in the contact area resisting moments (See Appendix A). These are greater the greater the length of the contact area is and the smaller the radius of the circle. These moments are negligible for automobiles (except when parking) but can be important for tractors.

For tracklaying and other brake-steered tractors this is the most important opposing moment but it has probably influence also on ordinary wheel tractors.

3. The resultant of outer forces on the tractor from implement, etc. does not always pass through the point of action of the resultant of the forces on the drivewheels and gives thereby a turning tendency which must be counteracted by steering forces.

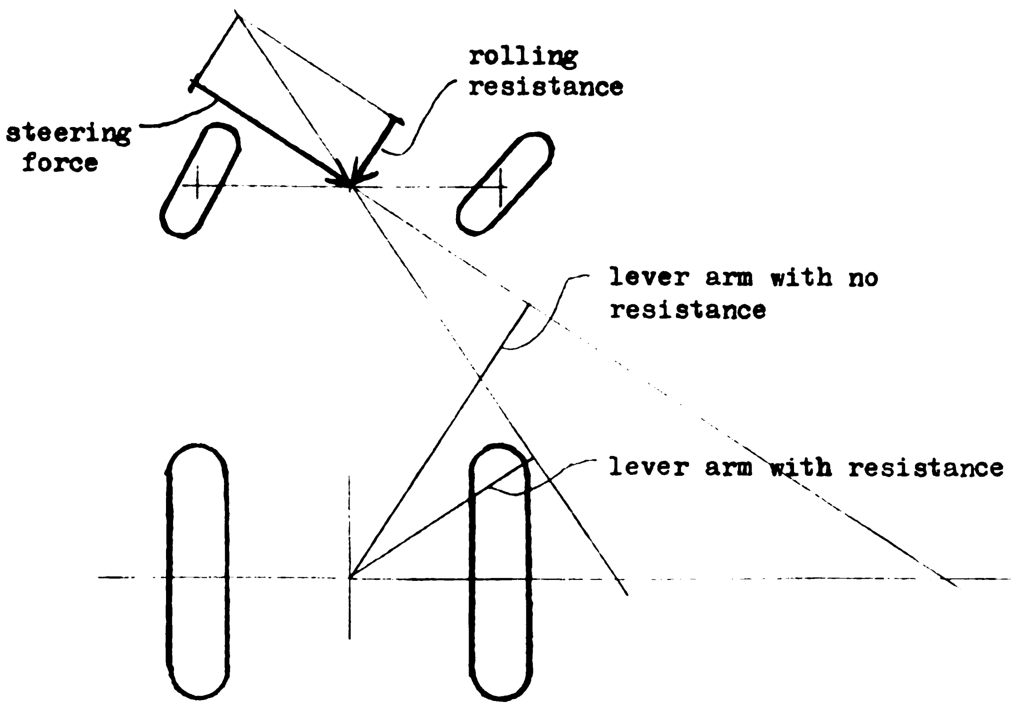
It ought to be observed in this connection that an attempt to make the implement move sidewise in a turn often causes the resultant draft to move far out to one side and at the same time to increase. Such turns should therefore be avoided because very large steering moments are needed to carry them through. The center of rotation for the whole unit must consequently be given attention.

4. The rolling resistance on the left and the right side of the vehicle might be unequal.

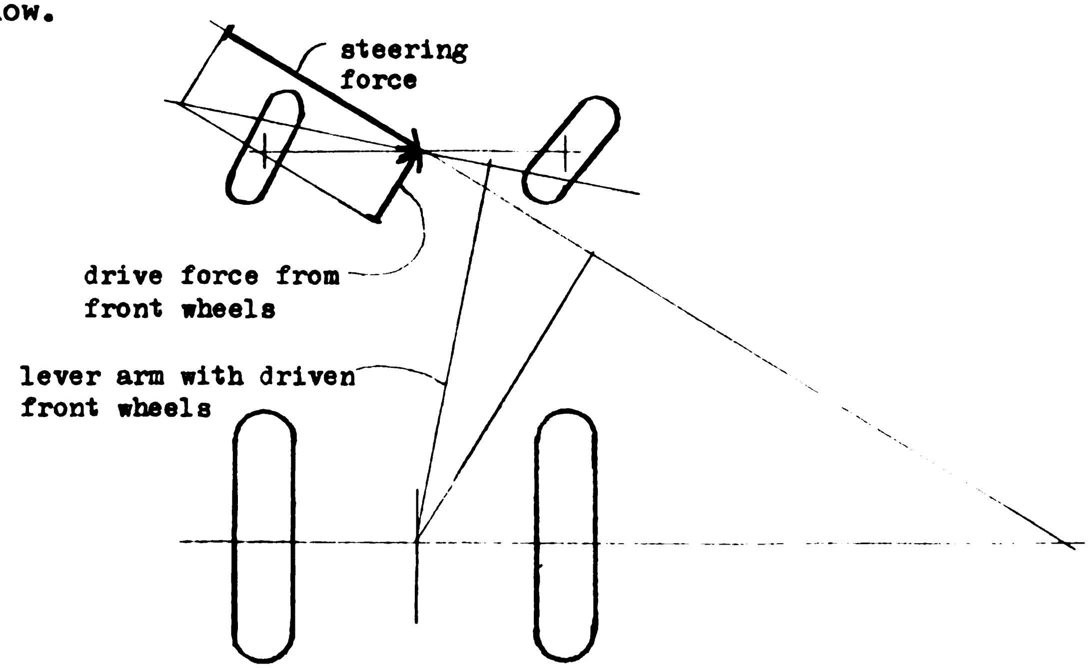
5. When there is a side force on the vehicle, as on a side slope, or in a curve with high velocity and centrifugal force, no steering moment is needed, but still a steering of the wheels must be made in order to give them sufficient slip angle to create the reactive side forces on the wheels.

Influence of Rolling Resistance on Steering Effectiveness

As mentioned in Appendix A the steering wheel stops rolling and thereby stops working as a steering wheel at a lower steering force, the higher the rolling resistance is. Even before that, however, the rolling resistance diminishes the steering effectiveness by decreasing the lever arm of the steering force on the steering wheels as shown in following picture.



If on the contrary the steering wheels were driven, the steering effectiveness would increase, as shown by the following figure. This explains one of the big advantages of all-wheel drive for vehicles working in the forest, in swamps or in snow.



Load on the Steering Wheels

Steering forces as well as driving forces originate in the contact between the wheel and the soil. These forces are in general proportional to the vertical load on the wheel. It would therefore seem to be most effective to put all or almost all weight on wheels, which were both driving and steering, or otherwise expressed to use the drivewheels for steering also.

One objection against such a method is that a steering force might reduce the driving force available from the same wheel. This is to a certain extent true, but of less importance, because steering and driving forces add as vectors, not numerically. Other reasons make this objection of still less importance for tractors.

Another more serious objection against steered drivewheels is that this makes a complicated drive mechanism necessary, especially if automobile steering is used as is at present most common. The steering radius is usually also increased. Therefore unpowered steering wheels are common on present tractors. In order not to make the drive effectiveness of the tractor too poor, the load on the steering wheels is kept relatively low. If other systems for steering are used, it is easier to combine steering and driving in the same wheels.

SECTION IV THE POWER UNIT

Preceeding sections have given the necessary information about the parts of the operational unit, the implement being described in Section II and the parts of the power unit in Section III. In this section this information will be integrated into the lay-out of a power unit with the aim to get the best possible operational effectiveness for a given operation or group of operations.

There are in the literature many discussions of different tractor types. A general discussion and comparison is made by Meyer (ref. 21). Discussions of the merits of certain types of power units are numerous.

Among historical reviews of the types of tractors which have been used, those made by Gray (ref. 15) and McColly (ref. 19) may be mentioned and an article by Moberg (ref. 23).

When making the lay-out the following steps may be included:

1. Determine the relative position of implement and wheels.
2. Determine which wheels should be driven and steered.
3. Determine place for operator.
4. Determine place for engine.
5. Check that the stability is within reasonable limits.
6. Evaluate the operational effectiveness of the combination.
7. Evaluate drive and steering effectiveness.
8. Further evaluations.

Before starting this it might, however, be desirable to study which wheel arrangements are possible and which have been used.

Chapter 11. Wheel Arrangements

It is possible to make power units with 1, 2, 3, 4 and more wheels and tractors with these numbers of wheels have also actually been made. Tractors with only one or two wheels need, however, with a few, theoretical exceptions some additional support to become stable. For fractional horsepower tractors this support can be supplied by the operator, who walks behind the tractor, but for all larger tractors it is not in line with the requirement on driver convenience to let him take the thrust of the engine. Such tractors should therefore not be made. In some cases two-wheel "tractors" are attached to their implement in such a way that the implement takes the thrust, but then they are not any more true two-wheel tractors, because the wheels or other supporting devices on the implement could be counted as wheels of the entire unit. In the future I will count such implement wheels as belonging to the power unit if the connection between the basic power unit and the implement is designed to take the thrust and the implement wheels are necessary to make the outfit stable. Examples of such combinations are found among heavy earth-moving equipment.

A summary of the variables in the wheel arrangements and of the possible values of each variable may look as in table

401. When combining these in all possible ways and only removing duplicates there seems to be more than 100 three-wheel solutions, and more than 300 four-wheel solutions when only wheel arrangement alternatives are counted. Only very few of these possibilities are really utilized.

Table 402 gives examples on some basic wheel arrangements. These examples can be carried further

by combining different drive and steering arrangements with the basic lay-outs.

The best wheel arrangement should be sought for every special use. Some general rules apply, however, for many cases. General rules concerning drive and steering effectiveness have been discussed earlier as has stability and these will therefore not be mentioned again here.

If the implement requires any considerable pull, this pull should be in the same longitudinal plane as the resultant force from the drivewheels. In tractors with an ordinary differential no wheel can usually give any appreciably higher pull than the others. The pull of the implement must therefore work on or close to the centerline of the drivewheels. This means that a plow, at least a multi-bottom plow, cannot be placed in front of the driving wheels, if one driving wheel is not to run on top of the plowed land, which is usually avoided.

Even if the implement is centrally attached, but mounted in front of the main drivewheels, this is not a good solution, because the force system is unstable. Any deviation from the

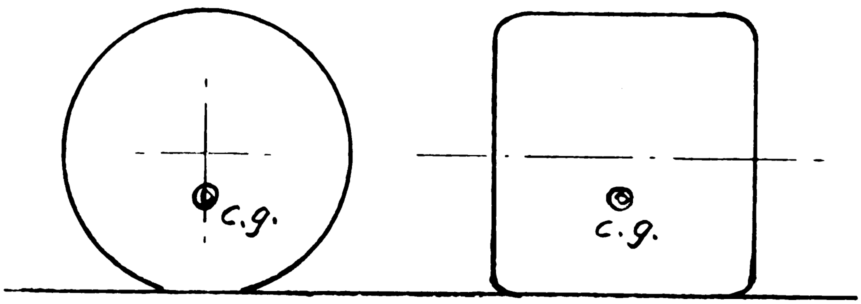
TABLE 401. VARIABLES IN WHEEL ARRANGEMENTS FOR A POWER UNIT.

Variable	Possible alternatives
Type of 'wheel'	Wheel, track, sled (ski)
Number of wheels	(1), (2), 3, 4, (5), 6 or more
Front wheels	1, 2, 3, 4, or more
Axles	(1), 2, 3, or more
Sidewise symmetry	Symmetric, not symmetric
Drivewheels, number	1, 2, 3, 4, (5), 6 or more
Drivewheels, position	Front, rear, combinations
Steering type	Automobile type, pivot, brake (differential)
Steering wheels	1, 2, 3, 4, (5), 6 or more
Steering wheels	Front, rear, combinations
Direction of travel in work	One, both.

TABLE 402. BASIC WHEEL ARRANGEMENTS FOR POWER UNITS.

Only alternatives, which at least theoretically are stable, are shown. Only one of left-hand and right-hand alternatives is shown.

1-wheel unit.



2-wheel units.

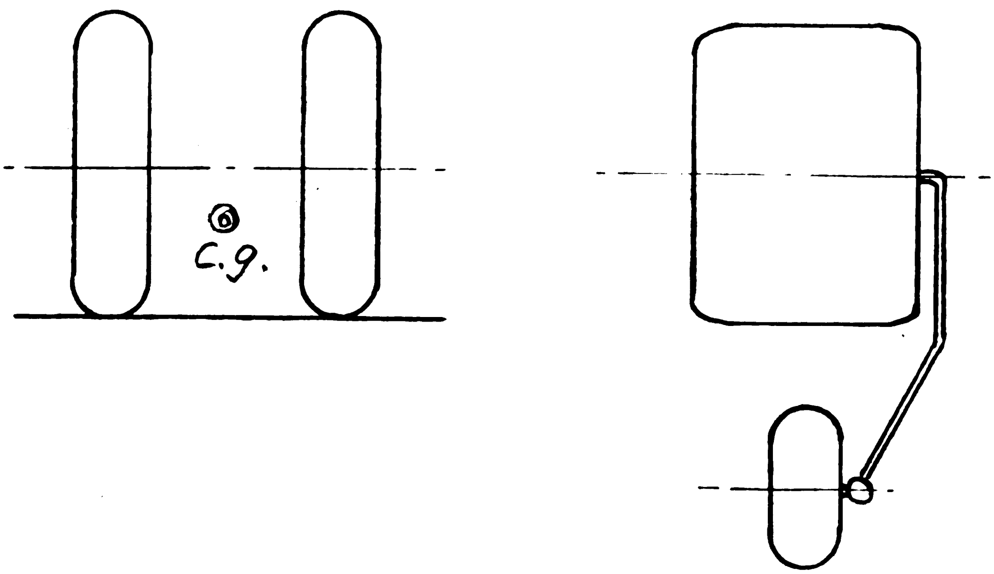
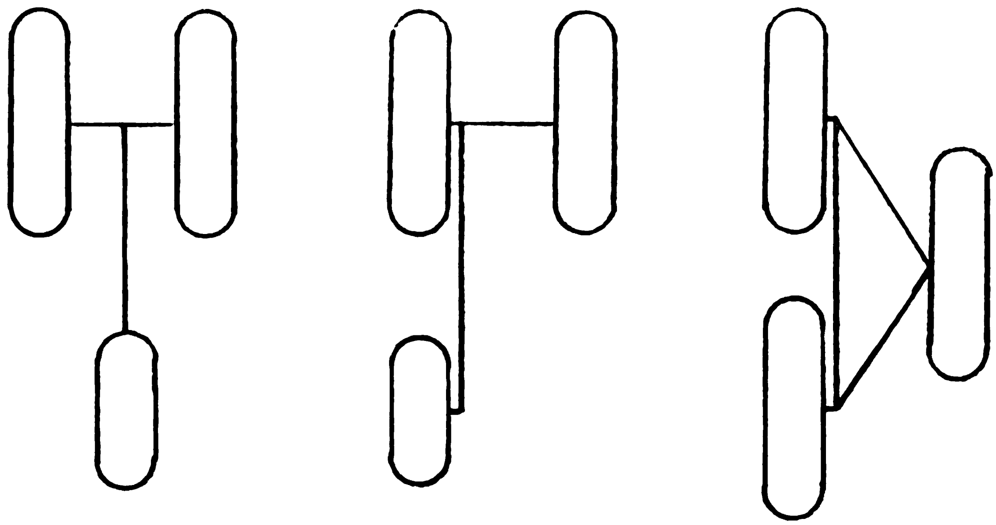


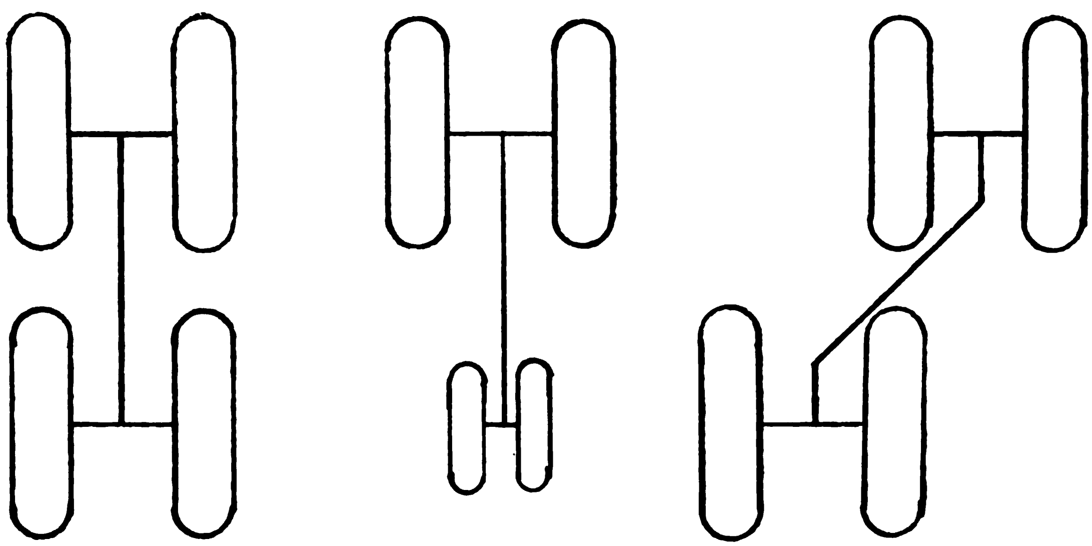
TABLE 402(cont.) BASIC WHEEL ARRANGEMENTS FOR POWER UNITS.

3-wheel units.



A B C

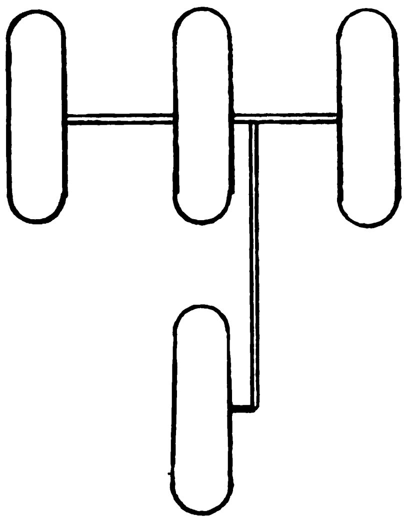
4-wheel units.



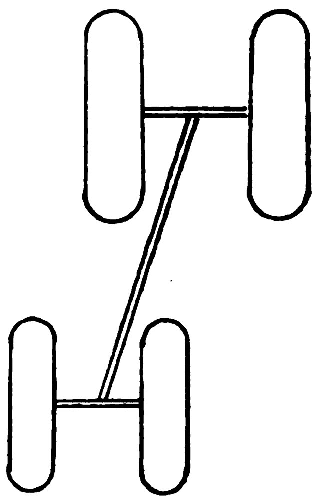
A B C

TABLE 402(cont.) BASIC WHEEL ARRANGEMENTS FOR POWER UNITS.

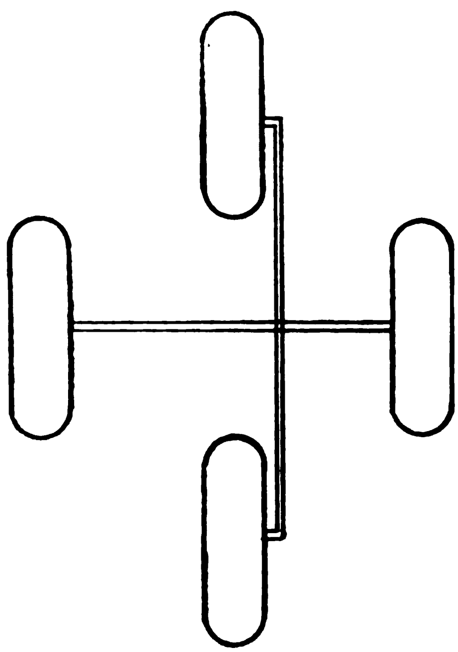
4-wheel units, cont.



D



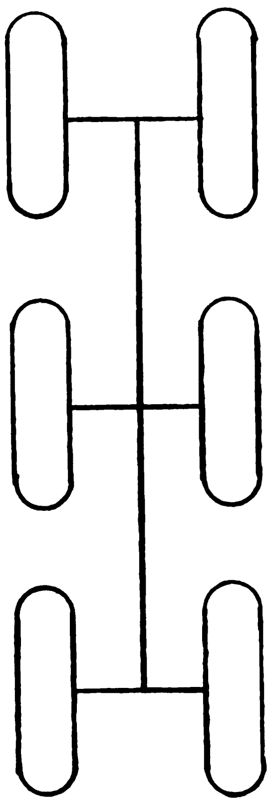
E



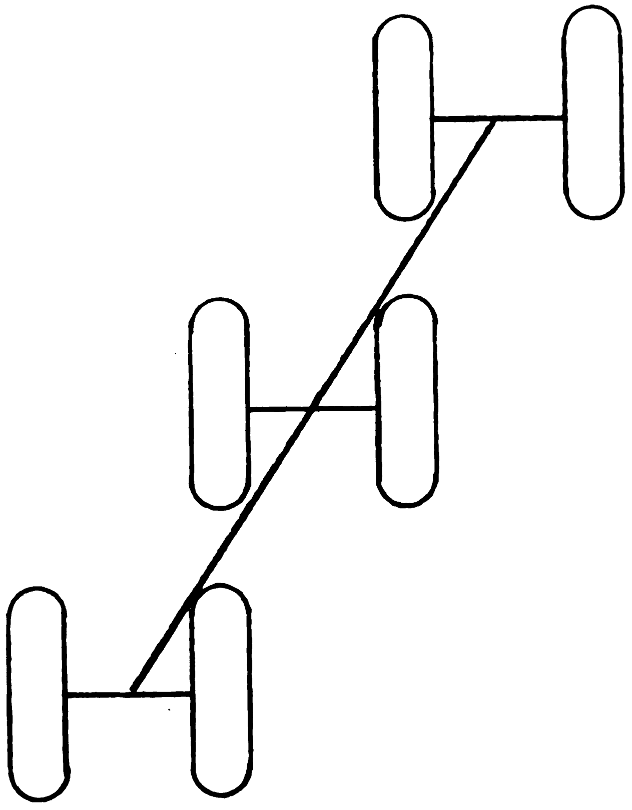
F

TABLE 402(cont.) BASIC WHEEL ARRANGEMENTS FOR POWER UNITS.

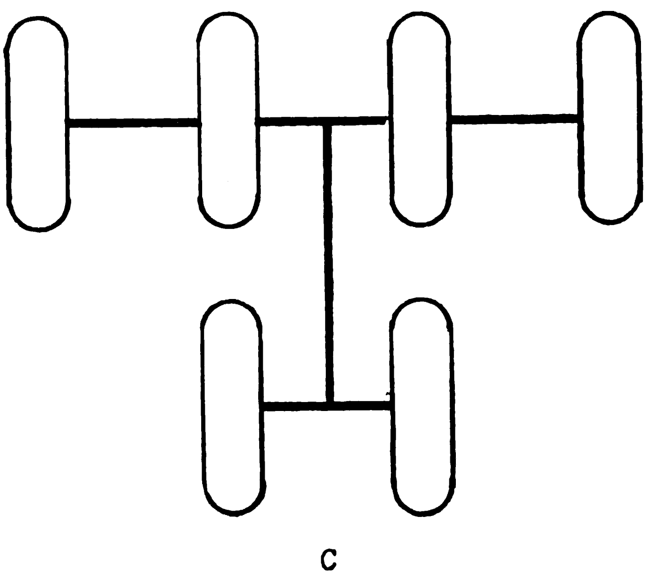
6-wheel units.



A



B



C

straight course causes a moment that tries to make the deviation still larger. When the load is attached behind the driving axle the draft tends to stabilize the power unit on a straight course.

The most important group of implements, requiring high pull, are the tillage implements. Their object is mainly to loosen the soil. It is then inconsequential to let the drivewheels follow behind the implement, because the drivewheels are heavily loaded and will compact the soil again. The tillage implements are therefore sometimes divided in two parts, one in front of the drivewheels and the other behind them, but this arrangement should be avoided if possible.

Most tractor wheels are chosen with regard to the part of the tractor weight they normally carry. The weight acts in the center of gravity of the tractor. The load distribution on the wheels is least changed when the implement load also acts in the center of gravity of the tractor. The further away from the center of gravity the extra load is applied, the greater will the changes in balance be, with corresponding poorer steerability, traction and roadability of the tractor. Therefore from the viewpoint of tractor stability and load carrying capacity centrally mid-mounted implements are the best and front and side-mounted implements the poorest.

Chapter 12. Individual Power Units

As mentioned earlier, the requirements of the implement has to be satisfied first of all if a good operational unit shall be found. These requirements can most easily be satisfied if individual power units are designed for each implement. This is consequently the first step of the evolution.

The implements are listed in tables 105-114 and the requirements and characteristics of the implements in tables 201-215. One way to use this information will be illustrated by a couple of examples.

Power Unit for Moldboard Plow

From table 210: (notations according to App. B)

implement weight W_{50}= 250 lb/ft

implement pull R_{52} = 1000 lb/ft

From table 201:

Field conditions: firm but sometimes slippery

Assume f_{opt} = 0.6 (anti-slip devices used when needed)

Assume 15% grade, i.e. $\sin \beta \approx 0.15$

The weight $W_0 + W_{50}$ can now be calculated as a function of η_l from equation 33b.

$$W_0 = \frac{1000}{0.6 \quad \eta_l} - 250$$

$$= \frac{1670}{\eta_l} - 250 \text{ lb/ft}$$

Assume tentatively a drivewheel loading effectiveness of 0.85

$$W_0 = 1720 \text{ lb/ft}$$

We intend to make a power unit for a 3 x 16 inch plow = 4 ft. working width.

$$W_0 + W_{50} = 7900 \text{ lb.}$$

This load may be carried by two 12 x 38 tires and one 7.50 x 20.

The drivewheels have to be in front of the plow in order to get even pull on both of them without any of them on plowed ground and to insure travel direction stability as discussed earlier.

The third wheel has to be placed behind the plow in order to insure constant plowing depth. (It should be remembered that the plow is supposed to be fully mounted with almost all of the reaction forces taken by wheels. The load on the landsides and other sliding surfaces should be kept at a minimum.)

Steering the rear wheel only is not effective enough. The simplest way of steering drive-wheels, pivot steering, can be used.

The wheel arrangement will then be as in the picture below. The dimensions of the plow are taken from table 210. The figure gives a wheelbase L = 123 in., tread 62 in. and implement position $x_{50} = 66 \text{ in.} = \frac{66}{123} = 0.54$

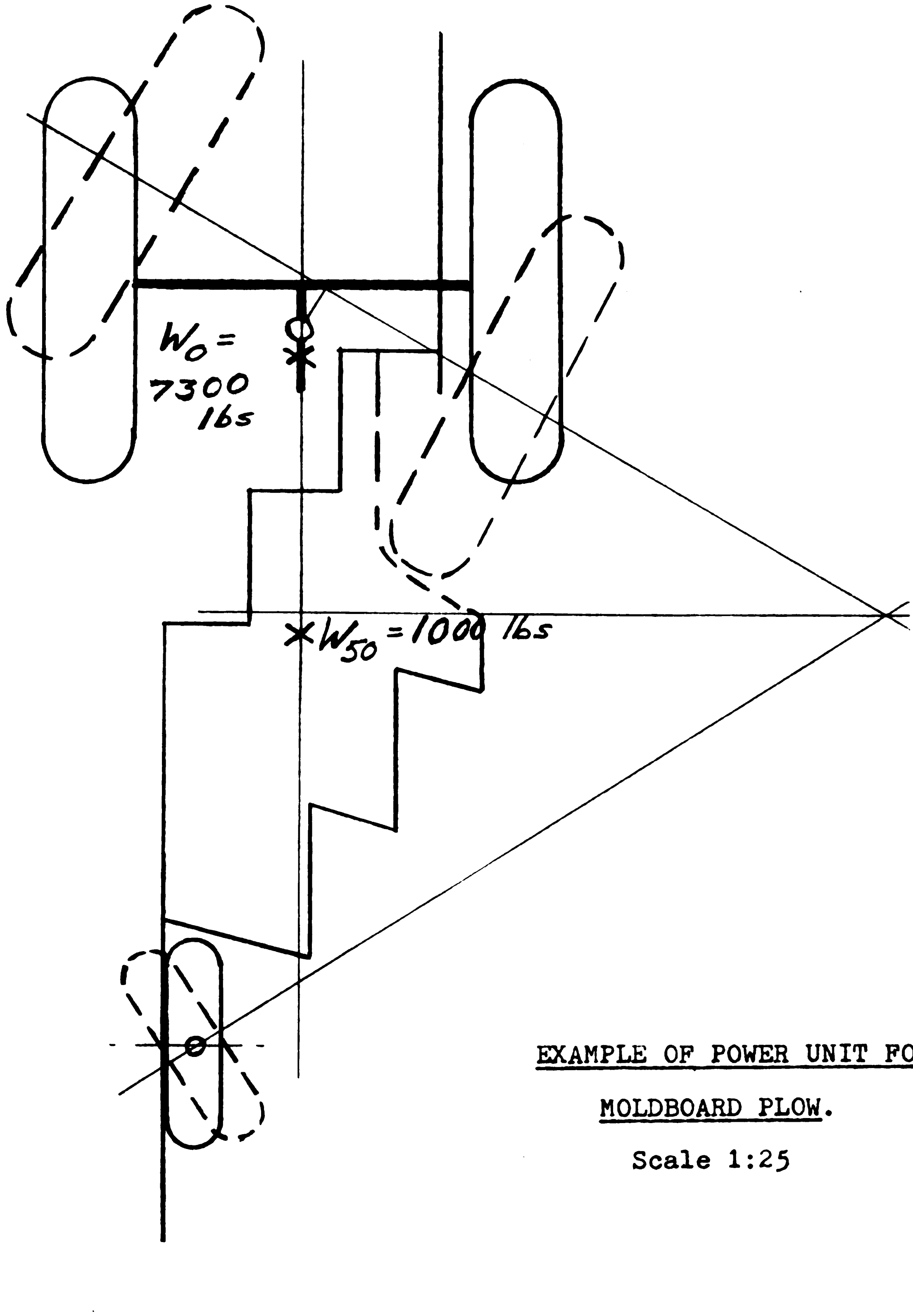
The position of the center of gravity of the power unit is determined by the stability. This being a front-wheel-driven power unit the longitudinal stability is least when the unit is backing. Assume distance of rolling resistance = 15 in. (hindrance, e.g. furrow wall).

$x_{11} = 123 - 15 = 108 \text{ in.} = 0.88$

$x_{21} = -2 \text{ in.} = -0.02$

$\ell = 0;$

$i = \frac{250}{1720} = 0.14$



EXAMPLE OF POWER UNIT FOR

MOLDBOARD PLOW.

Scale 1:25

$R_{52} = 0;$

$y_{52} = 0;$

This inserted in equation 36a gives for $\beta = 0$.

$x_0 \leqslant 0.93;$ Take $x_0 = 0.90 = 111$ in.

We can now calculate the actual drivewheel loading effectiveness for

$x_{11} = 123 + 3 = 126$ in. $= 1.02$

$x_{21} = 2$ in. $= 0.02$

$y_{52} = 3$ in. $= 0.02$ (height of the center of resistance of the implement)

$\ell = 0.1$ (10% of implement weight carried by landsides, shares, etc.)

$x_{51} = x_{50} = 0.54$

$f_1 = 0.6$

$f_2 = -0.1$

$\eta_\ell = 81\%$

This is less than assumed at the beginning of the calculations. The weight of the power unit therefore has to be increased to 7300 lb.

It should be mentioned that this weight 7300 lb. does not need to be all in the power unit proper but could partly consist of ballast placed elsewhere, e.g. advantageously on the plow. All that is required is that the power unit and the ballast together weigh 7300 lb. and that their common center of gravity is 12 inches behind the drive axle.

For a rough calculation the rolling resistance can be put equal to

$$0.1\ (1000 + 7300) = 830 \text{ lb.}$$

Total force on drive-wheel periphery is then

$4000 + 830 \approx 5000$ lb.

According to table 210 the maximum speed of plowing is around 5 mph. Corresponding engine power with a transmission efficiency of 0.9 is then 56 hp., which therefore is the maximum horsepower that can be utilized in this operational unit.

The figure below shows a power unit for a 6 x 16 inch plow. This has to have four-wheel drive.

A corresponding calculation for an ordinary tractor and three-bottom plow, using $\ell = 0.5$ gives $\eta_\ell = 64\%$.

The calculations for the plow power unit are probably made with unnecessary wide safety margins, because e.g. the values for draft are taken from plows with less favorable mounting system. The calculations show, however, how the basic data can be used. For better reliability the basic values must be better specified, giving corresponding values for plowing resistance, f_{opt} and x_1. Such a specification can be much easier done if a reliable soil value system can be found.

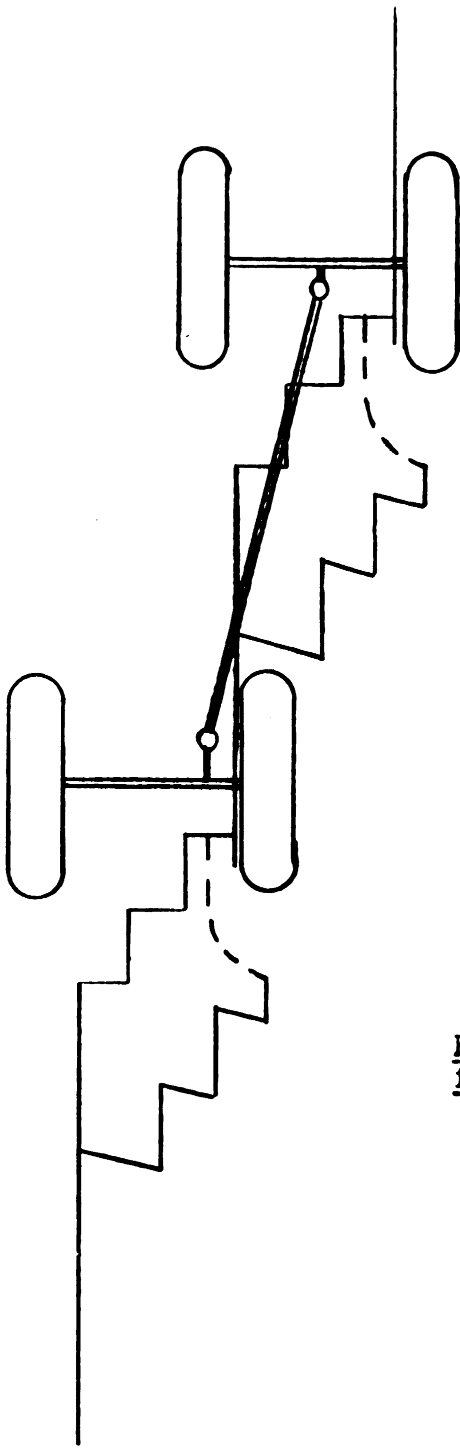
Power Unit for a Grain Drill

From table 210:

$W_{50} = 150$ lb/ft

$R_{52} = 75$ lb/ft

The grain drill consists of two main parts, the openers and the seed-metering devices being one and the hopper the other. Assume the weight of the openers and seed-meters being



<u>Example of power unit for 6-bottom moldboard plow.</u>

Scale 1:50

110 lb/ft and of the hopper 40 lb/ft. If the pull was calculated for 50 lb/ft grain in the hopper and the coefficient of rolling resistance 0.2, the pull of the openers should be 75 - 0.2 · 90 = 55 lb/ft. The data are consequently:

	Openers and seed-meters	Hopper and grain
Weight	W_{50} = 110 lb/ft	W_{50} = 40 + 100 lb/ft
Draft	R_{52} = 55 lb/ft	D_{52} = rolling resistance
Self-support	ℓ = 0.9	ℓ = 0

With $\eta_\ell = 0.65$ and $f_{opt} = 0.3$

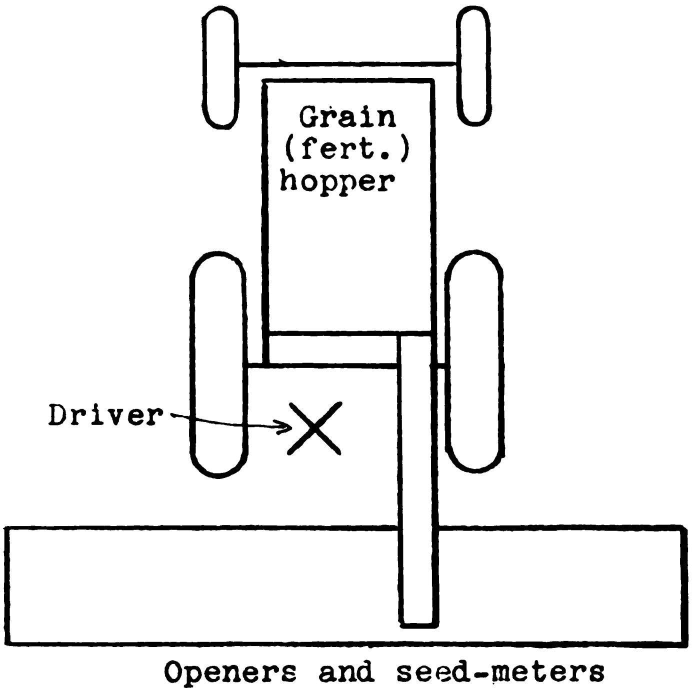
(no slippage wanted) a power unit for a 15 ft. drill would have (equation 33b)

$$W_0 = 15 \frac{55 + 250 \times 0.15}{0.3 \quad 0.65 \quad 0.99} - 250 = 15 \cdot 230 = 3500 \text{ lb.}$$

The arrangement is shown in the sketch below.

EXAMPLE OF POWER UNIT FOR GRAIN DRILL

Scale 1:50



Power Units for Other Implements

Using the same basic procedure as in the two examples given, the most suitable power unit can be found for other implements.

Different possible arrangements can easily be compared by using cardboard templates of the parts involved as have been used in the examples here. The templates were made to scale 1:25 and showed the contours of the part in the horizontal plane. They could easily be moved around on a paper with a coordinate system, drawn to the same scale. In that way the actual coordinates could be read directly when the parts (templates) had been located in the right place.

Chapter 13. Power Unit for More Than One Implement.

From a study of individual power units it can be seen that the same type of power unit can be used for more than one implement, even if the dimensions of the power unit might not be the same. This is, for instance, the case for fertilizer distributor, grain drill and sprayer, where the implement consists of a ramp for distributing, placed behind the power unit and a container for the material being distributed, placed at the center of the power unit.

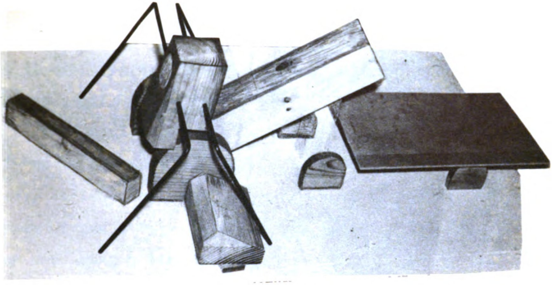
These power units for two or more implements are closer to reality and should therefore be more carefully checked for the practical possibility of the arrangement. A way to do this is to make wooden blocks of the important parts of implement and power unit to some scale, e.g. 1:10. The blocks should indicate the space needed for each part including all transmissions, etc. belonging to it. The figure below shows some such blocks and an arrangement of them.

Even if the number of power units can be reduced in this way there are still more types than can be economically used. A further reduction of types is therefore necessary, even if the reduction probably does not need to be reduced down to a single, general-purpose type. This is discussed in the next paragraph.

When reducing the number of types, this means that a compromise must be made between the requirements of the different implements which the power unit shall serve. Most consideration must then be given to the most important implement. Different measures of the importance of the implements were discussed in chapter 4 and can be used at this time.

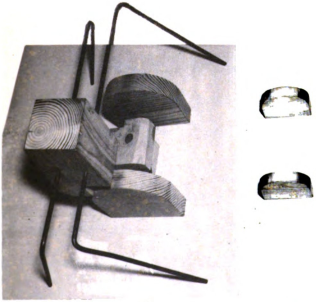
One detail may be mentioned here. One of the implements in a group might require a heavier power unit than the others. It is then logical to place as much as possible of this extra weight in the implement and not in the power unit. Savings in fuel economy and less soil compaction will be the result of such a proper adjustment of the weight.

This section has shown some definite proposals of power unit design, to which many objections might be raised. They are, however, not given as final answers to the question, which would have been very pretentious, but as examples of a way to attack the problem, and in the author's opinion, the best way to attack it. Using this method, somebody else with



side delivery rake | pick-up device | baling chamber | wagon (should have sides)

BLOCK MODEL OF POWER UNIT WITH PICK-UP OUTFIT.



driver's cab (supporting legs only in model) | drivewheel | engine | drivewheel | steering wheels

POWER UNIT FOR THE BALER.

better knowledge of all facts, could certainly find better solutions.

<u>Is It Absolutely Needed That the Power Unit Can Perform Every Operation on the Farm?</u>

The opinion is sometimes expressed that the farm cannot afford to buy machines, made especially for a certain operation, at least not more expensive machines. Some of the new types of power units that are available today cannot be used for more than a limited number of operations, and this has been given as the most important reason for their relatively small popularity.

There is, however, an increasing demand for self-propelled combines, in spite of the fact that these are both expensive and specialized. A certain demand for other self-propelled harvesting machines has also been felt. This indicates that there might be a market for a power unit that could make more than one harvesting machine self-propelled, even if the power unit could not be used for other farming operations.

Furthermore, the farm of today usually has more than one tractor. The farmer therefore does not have any more the same need for a tractor that can perform all operations, i.e. that all tractors should be of the same general, all-purpose type. On the contrary, there seems to be a good reason, that different types of power units be used, each specially fitted for a certain group of operations. A better efficiency could be expected with such a solution, because the all-purpose tractor must be a compromise between very differing demands.

A reason against differentiated tractor types, though of minor importance, could be that the different power units on a farm could not be used as spares for each other to the same extent as now. Neither would it be possible to use the new tractor for some operations, even if it was not busy, because the old tractor was the only one, made for that type of implement.

SUMMARY AND FURTHER INVESTIGATIONS

Summary

All farming operations are performed by implements, which require power of some kind. For a long time this power was supplied by man but it was not until man could employ other power sources for his implements that he could increase his productivity and thereby his standard of living by any appreciable amount.

The most important, early power source was the horse or other animals; and implements were made which would fit this power source. When mechanical power began being used besides animal power, the implements were basically the same as used earlier for the reason, among others, that the implements often had to be used alternately with mechanical and animal power and also because special tractor implements had not been developed. The function of the mechanical power unit, therefore simulated the function of the horse to a very high degree.

When now the horse in many countries is without importance as a power source, pure tractor implements could be developed. A basic difference between the horse and the mechanical power unit should thereby be observed. Contrary to the horse, the mechanical power unit can be adjusted to fit the implement as well as the implement can be adjusted to utilize the mechanical power unit in the best way. Implements and power unit should, therefore, not be developed separately but at the same time and as one operational unit.

One of the fundamental preparations for the design of a power unit should consequently be a study of what the implements require of their power unit. These requirements are of two kinds; namely, those which are dictated by the operation itself and the product involved and those which mainly originate from the design of the implement. The first kind of requirements is called the operational requirements of the implement; the second is called the technical requirements.

Some existing implements perform several operations at one time. Each such operation should be studied separately when determining the requirements of the implements in order to connect the requirement only to the part where it belongs. This makes it easier also to discuss other combinations of operations than is common at present.

Requirements which could be listed as operational are those related to field conditions, quantities of product involved, time available for operation, supervision of function needed, adjustment of implement in work, height control of implement in work and on headlands, accuracy of steering of implement and power unit in work, and special factors affecting the position of the implement -- for instance, if it should be in front of or behind the wheels. Operational requirements are briefly listed in tables 201-206.

The technical requirements of the implements are connected to such factors as size, weight and outer dimensions, draft, power type and amount of power, if rotational power or pull is needed, vertical forces (weight transfer), speed and speed adjustment and capacity. Technical requirements are listed in tables 210-215. These tables are very imcomplete because values are not available.

The operational requirements will usually not change very fast because they are connected to the crop and the methods used in producing the crop. Most technical requirements, being connected to the implement design, will change must faster.

Requirements mentioned earlier are all connected to the implements and their operation. In order to make the unit implement and tractor an effective unit, certain functional requirements connected to the tractor parts have to be fulfilled also. There are many such requirements but the most important ones, affecting the general shape of the power unit, are the requirements on good drive effectiveness, good steering effectiveness and sufficient stability. Driver position and method for connecting the implements to the power unit should also be considered.

The drive effectiveness is defined as the ratio between the actual useful pull and the highest possible pull that could be exerted by an operational unit (implement + tractor) of the same weight on the same type of ground and when the implement works in the same manner. The drive effectiveness has two components -- the drivewheel loading effectiveness and the ground grip effectiveness. The drivewheel loading effectiveness indicates how effectively the available vertical forces are utilized for loading the drivewheels and thereby producing pull. Equations for the drivewheel loading effectiveness are given in chapter 9. The drivewheel loading effectiveness for a rear-wheel driven power unit is favorably influenced if the weight of power unit and implement is placed far back, by a pull high above the ground, by a long distance of rolling resistance, by fully-mounted implements, etc. The limit for increasing the drivewheel loading effectiveness for a two-wheel-drive power unit is usually set by the stability of the unit.

The ground grip effectiveness is intended to indicate the effectiveness of producing pull, i.e., the effectiveness of the force transmission between the wheel and the soil, when the size of the wheel load is fixed. It is usually favorably influenced by relatively low total load on a given wheel, by low inflation pressure, and by running the wheel in an earlier wheeltrack, where the rolling resistance usually is smaller and the strength of the soil increased through compaction. Increasing the load on a given wheel generally decreases the ground grip effectiveness. This fact limits the pull that can be produced by an individual wheel because the size of tires is limited for design reasons. The ground grip effectiveness has not been observed enough in present research and design work.

Both longitudinal and lateral stability are based on a suitable positioning of the centers of gravity of the power unit and the implement relative to the wheels or other supporting media. Both stabilities are adversely affected on a slope and in a curve by high positions of the centers of gravity.

The longitudinal stability is further decreased by the height of the pull above the ground, by increasing distance of rolling resistance and by inertia forces, especially the horizontal acceleration force on the operational unit and the rotational inertia moments on the drivewheel. The lateral stability is higher for a four-wheel power unit than for a three-wheel unit, and this superiority is better the higher the joint between the front axle and the rest of the power unit is placed.

The steering effectiveness is influenced by the system for steering but the relative merits of different systems have not been investigated. The steering effectiveness is higher for a driven wheel than for an unpowered wheel and higher for a steering wheel with high load than for a lightly loaded wheel. The movement of the implement in a turn must be observed because it could have an important influence on the steering.

The operational and technical requirements mentioned above give the basis for the design of the power unit. One procedure for making the design has been outlined in section IV. It starts from the concept that the self-propelled implement is or can be made the most effective operational unit. The first step in the procedure is therefore to design individual power units for each implement, where the requirements of only one implement are satisfied, as far as possible. The factors to be determined for this initial design are, for instance, wheel arrangement, driver position, weight, positions of center of gravity, steering system and engine horsepower. A detailed design is not needed at this stage.

The second step is to find power units for more than one implement and for combinations of implements. Combinations, which are of value, are indicated in tables 105-114. In some cases a power unit found in the first step can be used as it is for more than one implement; in other cases, the new power unit can be found by combining common features of the individual power units. When making combinations, the capacities of the implements and the power unit in the combination must be matched. It is not always possible to fully satisfy all requirements of the implements in a combination. For the decision on which requirements could be neglected, knowledge about the importance of the implements is essential. The importance of an implement can be measured by the area covered, the frequency of the use of the implement, the value of the product involved, etc. This is discussed in chapter 4.

It is unlikely that a power unit can be found which can be used for all implements without severe sacrifices on the operational effectiveness of at least some of the implements. Such a general purpose tractor is, however, not absolutely needed because a future farm could very well have special tillage tractors, harvest tractors, etc. Higher operational effectiveness would likely be the result of such a diversification of the power unit design.

Further Investigations on This Subject

This study is mainly a framework, intended to show what basic information is needed to make a power unit layout and also to show a method of finding a suitable power unit. Each of the parts of the study could probably favorably be made objects for further study. Among the subjects I would like to mention are the following:

1. The listed requirements of the operations and the implements are only incompletely described. The technical requirements should be especially checked because the values now given contain factors which are not inherent in the basic operation or implement. Parasitic pull is included in some draft figures, carrying wheels, etc., in the weight figures, etc. A more thorough study of the literature would probably give more information here but more new research must also be made. It is thereby important that the basic functions are studied without irrelevant factors being included.

2. Among the technical requirements more attention than now should be given to the vertical forces that can or must be applied to an implement. For good drivewheel loading effectiveness these forces are essential. It is now possible to utilize them when the implements are mounted.

3. The values for draft and power consumption as well as for traction and rolling resistance should, as far as possible, be related to properties in the product or the ground, not to the implements. A reliable soil value system is one of the necessary ingredients in this. If possible, soil values should be given for the separate operations.

4. Among mechanical relationships which should be studied further in order to make this method of design more reliable, should be mentioned:

a. ground grip effectiveness

b. optimum load and power on a tire

c. the distance of rolling resistance, x_1, for both ordinary and exceptional conditions

d. the behavior of a tire under lateral load

e. the mechanics of stability for both the power unit alone and for the combination of power unit and implement

f. the mechanics of steering for both power unit and combination

5. A thorough investigation should be made to find the best individual power unit for each implement. Then power units for combinations of implements should also be found. This would indicate the direction for the evolution of the present tractors. Such investigations would have to be repeated with regular intervals as more information becomes available and the outer conditions are changed.

6. This study has been limited to existing implements. Some of these implements do not utilize the power unit very well. Better substitutes for them should be sought with due regard taken to the possibilities of the mechanical power unit. When such implements are found, however, the method shown here can be used to find out what type of power unit the new implement requires.

7. Consideration should be given now and then to entirely different types of powered farming (circular fields, permanent "tracks", cable-operated implements, etc.).

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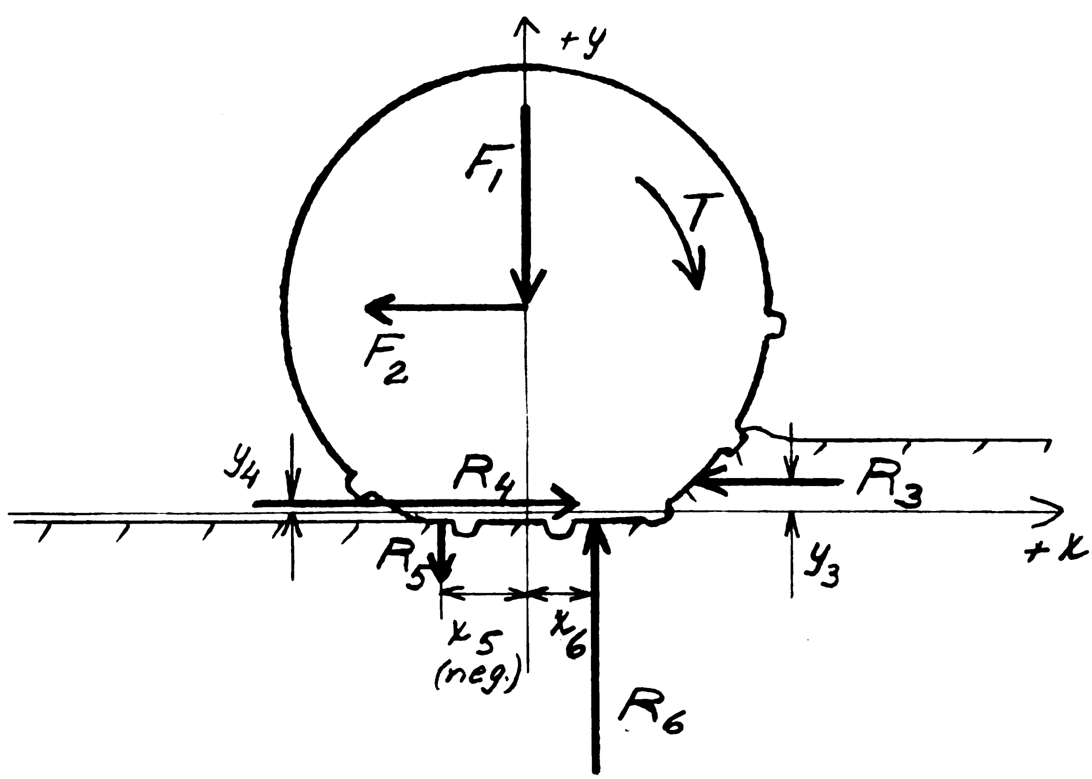
APPENDIX A. THE FORCES BETWEEN A WHEEL AND THE GROUND.

The discussion of the drive and the steering effectiveness and of the stability of the power unit is based on the laws of mechanics, regarding forces, etc. on the unit. The most important of the forces are the forces between the wheels and the ground because they enter into all equations. A detailed study of these forces is therefore justified.

Resultant Forces in the Wheel Plane

The forces on the wheel in the contact between the wheel and the ground are sometimes (ref. 2, p. 284) represented by the four forces R_3, R_4, R_5 and R_6 as indicated in the figure below.



R_3 is "pure rolling resistance"

R_4 is reaction against driving torque

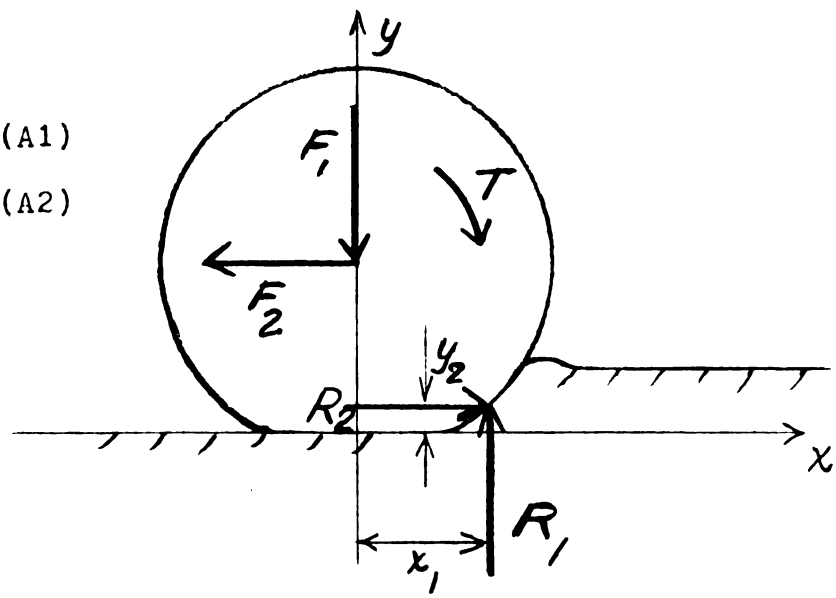
R_5 is downward reaction on the wheel, especially its lugs. It is often = 0.

R_6 is supporting reaction on the wheel

Even if these forces are helpful in explaining the forces at the contact between soil and wheel, they are difficult to determine separately and they are not needed to represent the contact forces. The four forces can in fact always be replaced by one single force or by one vertical and one horizontal force, working in the same point. The latter system is shown in the picture below, where

$$R_1 = R_6 - R_5 \quad \text{(A1)}$$

$$R_2 = R_4 - R_3 \quad \text{(A2)}$$



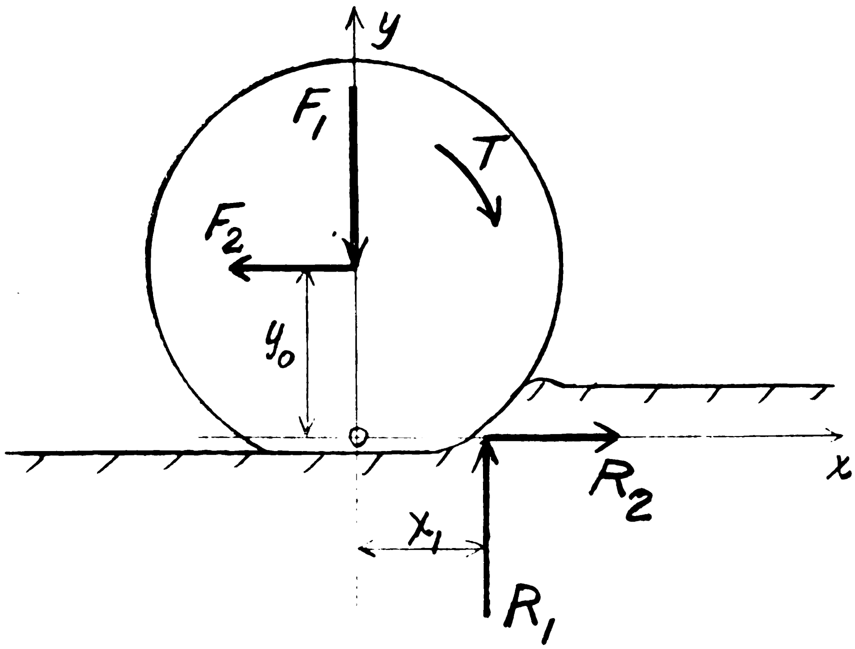
When we compare the two-force system and the four-force system, we find that they give the same resultant force on the wheel, but that there is a difference in the moment of size

$$R_6x_6 + R_3y_3 - R_4y_4 - R_5x_5 - R_1x_1 + R_2y_2 =$$
$$R_6(x_6-x_1) - R_5(x_5-x_1) - R_4(y_4-y_2) + R_3(y_3-y_2)$$

It is, however, possible to simplify this system further as shown in the picture below. Here y_2 is given a fixed value = 0, and we want to find the value of x_1 which makes the difference in moment = 0, i.e. which makes this system entirely equivalent to the original four-force system. This value of x_1 is

$$x_1 = x_6\frac{1 - \frac{R_5}{R_6}\frac{x_5}{x_6}}{1 - \frac{R_5}{R_6}} + \frac{R_3y_3 - R_4y_4}{R_6 - R_5} \qquad \text{(A3)}$$

In most cases x_5 is negative but R_5 close to 0. R_6 is larger than any other force, y_3 is equal to or smaller than x_6 and y_4 is small. Then x_1 is slightly larger than x_6.



A method of determining x_1 experimentally will be described later.

In the future treatment I will, where nothing else is said, use the two forces R_1 and R_2 working at the same point

$x = x_1$ and $y = 0$. This will always be a true representation of the forces, provided the right value for x_1 is used.

The coefficient of net traction.

The ratio F_2/F_1 is given the symbol f, where f is the coefficient of net traction. Two special values of f are f_{opt} and f_{res}.

f_{opt} is the highest practical value of the coefficient of net traction for a given combination of wheel and soil. 'Practical' means in this case giving the highest power efficiency or giving a fixed slip for a certain load. Higher f-values than f_{opt} can usually be found, but with sacrifice of power efficiency.

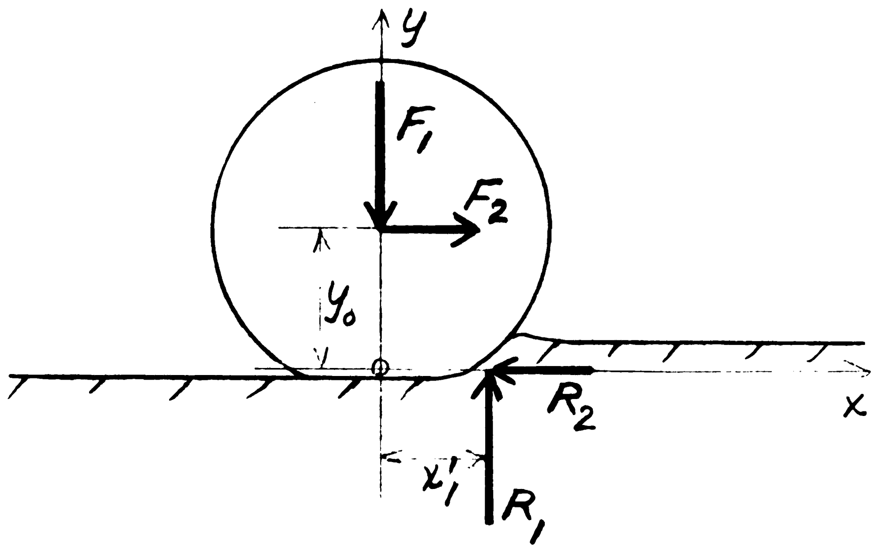
f_{res} is usually called coefficient of rolling resistance. It is a negative f-value, $-f = f_{res} = \frac{-F_2}{F_1}$ where F_2 and F_1 are measured on level ground, when no torque is applied to the wheel. A relation between f_{res} and x_1 can be found as shown on page A5.

f-values should always be given together with information about the tire, the soil, the slip and the inflation, for which they apply.

Discussion of x_1

From the preceeding chapter it might be remembered, that x_1 as it is used here, is defined as the x-coordinate of the intersection of the x-axis and the resultant of the soil forces on the wheel. The x-axis lies in the ground plane only for a wheel with rated load and rated inflation on hard ground. This means that the point $(x_1; 0)$ is not necessarily a point on the wheel. It also means that it has nothing to do with the rolling radius of the wheel (except on hard ground).

We first try to find a relation between it and the coefficient of rolling resistance. The rolling resistance is usually defined as the force needed to pull the loaded wheel, when no torque is applied. The coefficient of rolling resistance, f_{res}, is defined as the ratio between the rolling resistance and the vertical load carried by the soil or the vertical load on the wheel, including the weight of the wheel itself. This is shown in the picture below.



The equilibrium equations for this special case are:

$F_1 = R_1 \qquad F_2 = R_2 \qquad x_1' R_1 = F_2 y_0$

and $f_{res} = \dfrac{F_2}{F_1}$

This gives:

$$x_1' = \frac{F_2}{F_1} y_0 = f_{res} y_0 \qquad (A4)$$

The special value of x_1 discussed here has been denoted x_1' in order to show that it is a fixed value, which theoretically applies only, when the torque on the wheel is zero.

y_0 is a fixed value, determined as the axle height for the loaded wheel on hard surface. It is exactly known and therefore x_1' can also be exactly calculated.

Because y_0 is close to D/2, equation A4 can approximately be written:

$$x_1' \approx f_{res}\frac{D}{2}$$

Bekker (ref. 4) has theoretically derived for a rigid wheel on soft ground (equations 182, 183 and 184)

$$F_2 = \text{const. } F_1^{\,2}\, D^{-1} \text{ or } F_2 = \text{const } F_1^{\frac{3}{2}}\, D^{-\frac{3}{4}} \text{ or}$$

$$F_2 = \text{const } F_1^{\frac{4}{3}}\, D^{-\frac{2}{3}}$$

which gives

$$f_{res} = \text{const } F_1\, D^{-1} \text{ or } f_{res} = \text{const } F_1^{\frac{1}{2}}\, D^{-\frac{3}{4}} \text{ or}$$

$$f_{res} = \text{const } F_1^{\frac{1}{3}}\, D^{-\frac{2}{3}}$$

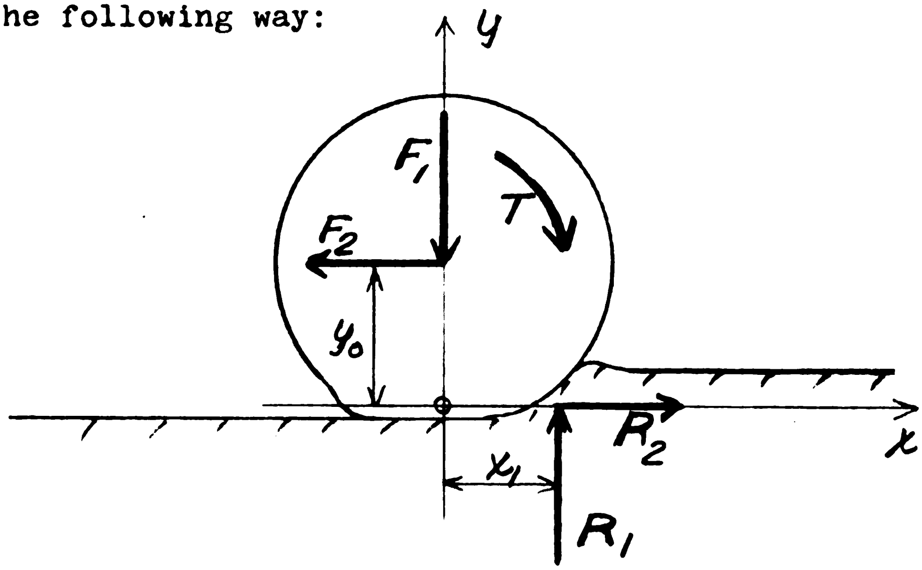
$$x_1' = \text{const } F_1 \text{ or } x_1' = \text{const } F_1^{\frac{1}{2}}\, D^{\frac{1}{4}} \text{ or}$$

$$x_1' = \text{const } F_1^{\frac{1}{3}}\, D^{\frac{1}{3}}$$

This shows that theoretically x_1' varies equally with the load as f_{res} and less than f_{res} with the wheel diameter. It should therefore be better suited to represent the rolling resistance than f_{res}. Both x_1' and f_{res} will, however, be used in the following. Incidentally, it may be mentioned that rolling resistance for a steel wheel on a steel track is given as a distance x_1', not as a ratio f_{res}.

When a torque is applied to the wheel, the value of x_1 might change, but no research information on this is yet available.

x_1 can be determined experimentally for all values of the torque in the following way:



$\Sigma \rightarrow : R_2 = F_2$

$\Sigma \uparrow : R_1 = F_1$

$\Sigma \curvearrowright : T - F_2 y_0 - R_1 x_1 = 0$

$$x_1 = \frac{T - F_2 y_0}{F_1} \qquad (A5)$$

So far all factors included can be measured with good accuracy and x_1 determined.

In order to relate this value for x_1 to x_1' or f_{res} we partly transform the expression for x_1 to the four-force system (page A1). Using the definition of $R_4 = \frac{T}{y_0 - y_4}$ $R_3 = R_4 - R_2$ and $R_2 = F_2$ we get

$$x_1 = \frac{R_4 (y_0 - y_4) - (R_4 - R_3)\, y_0}{F_1} = \frac{R_3 y_0 - R_4 y_4}{F_1}$$

If y_4 is small enough to be neglected

$$x_1 = \frac{R_3 y_0}{F_1} = f''_{res} y_0 \approx f''_{res} \frac{D}{2} \qquad \text{as before.}$$

x_1 might apparently also in this case be considered a measure of rolling resistance, but it must be remembered that its value might now be another than when there is no torque. Work done by Walters-Worthington (ref. 30) indicates a considerable increase in x_1 with increasing slip.

Table A1 shows some values for x_1 calculated from tests, performed by the Ford Motor Co., Birmingham, Michigan in which F_1,F_2 and T were measured. The influence of such factors as axle load, slip or torque seems here to be small, or at least much smaller than the influence of irregularities in the field.

In Table A2 are given theoretical values for x_1 for some unorthodox cases of wheel-ground contact as an illustration of how x_1 might vary and of how it is influenced by e.g. F_2 in these cases. The x_1 values given indicate the position when enough torque is applied to utilize f_{opt}, i.e. to make the wheel start spinning. The values will be of special interest in the discussion of the stability of the power unit.

Table A1. Examples on distance of rolling resistance, x_1

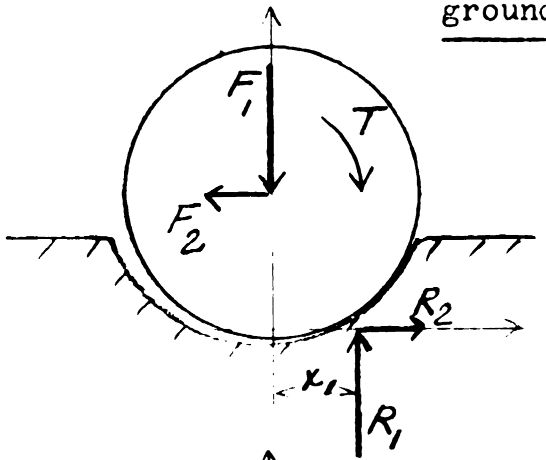
Calculated from tests made by Ford Motor Co., August 1957.

A rear-wheel driven tractor and a tandem tractor was used.

Tractor	Ordinary				Tandem			
Wheel	Front 5.50 x 16		Rear 11 x 28		Front 11 x 28		Rear 11 x 28	
Ave. load in work, lbs.	925		3385		4630		3880	
	Mean and standard deviation of x_1 ft.*							
Ground	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Asphalt, test track	0.024	0.077	-0.015	0.054	-0.025	0.037	0.007	0.149
Airfield sod	0.134	0.099	0.063	0.079	0.209	0.084	0.090	0.077
Plowed and disked field, hard clods	0.256	0.137	0.375	0.121	0.343	0.118	0.240	0.076
Plowed field large hard clods	0.253	0.136	0.335	0.144	0.430	0.104	0.297	0.093

*The deviation is due to both irregularities in the field, different load and slip and to deviations in the instrumentation. The means are accurate within less than ± 0.040 ft S.D.

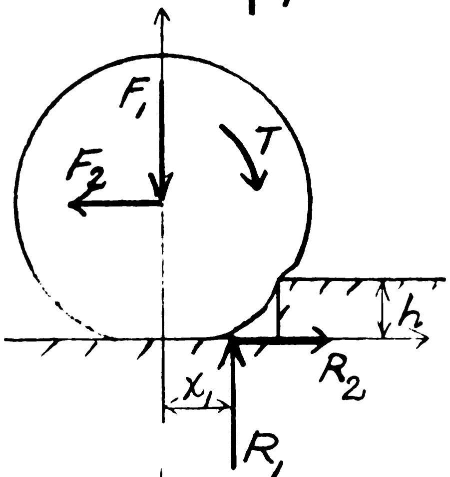
Table A2. Calculated distance x_1 for special cases of wheel-ground contact.



Dug-down wheel

Assume $f_{opt} = 0.6$ and $f_{res} = 0.1$

F_2/F_1	=	0.6	0.4	0.2	0
$\frac{x_1}{D/2}$	=	0.1	0.25	0.42	0.6

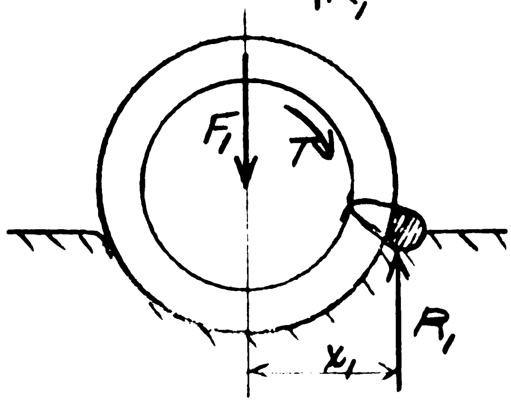


Wheel passing hindrance

Assume $f_{opt} = 0.8$ and $f_{res} = 0.05$

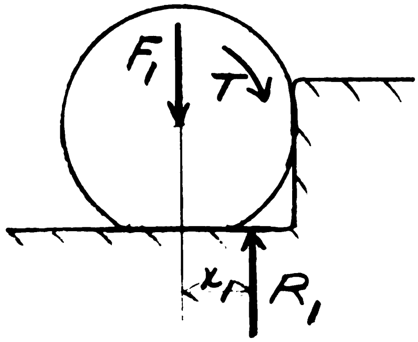
F_2/F_1	=	0.8	0.4	0
$\frac{x_1}{D/2}$	=	0.05	0.33	0.67
$\frac{h}{D/2}$	=	0	0.03	0.22

The impression in the tire is assumed negligible.



Log attached to wheel with chain, etc.

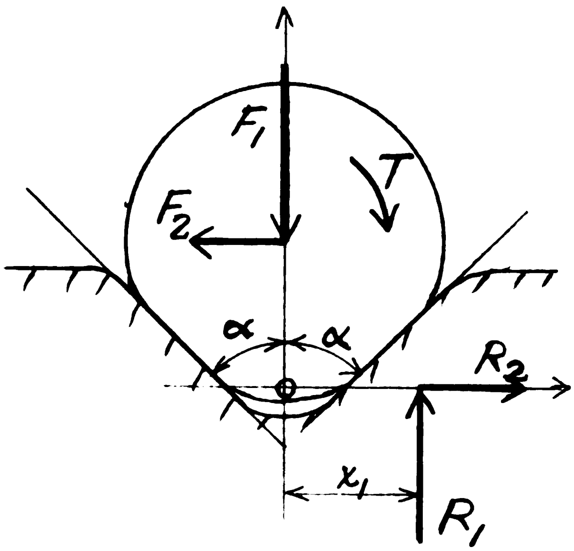
Maximum $x_1 \approx D/2$.



Wheel against high hindrance

$$\frac{x_1}{D/2} = f_{opt}$$

Table A2. cont.

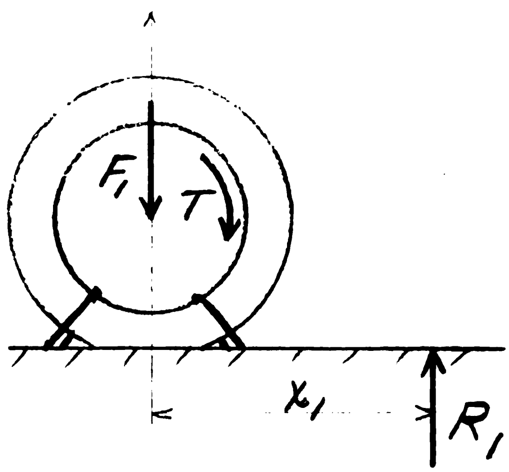


Wheel in a ditch (with hard sides)

Assume f_{opt} = 0.6 and f_{res} = 0.1

α	=	60°	45°	30°
$\frac{x_1}{D/2}$ =	F_2/F_1 = 0	0.73	0.89	1.27
	= 0.3	0.32	0.43	0.81
	= 0.6	--	0.31	0.55

Another assumption is that the wheel does not move. As soon as it moves, x_1 is the same as for a dug-down wheel.



Wheel, fixed to the ground with chains, by frost, etc.

$x_1 = T/F_1$

Stresses in the Soil in the Wheel-Ground Contact Area.

Pressures and Sinkage

The capacity of the soil to support an unpowered wheel has by Bekker (ref. 4) been expressed thus

$$p = \left(\frac{k_c}{b} + k_\varphi\right) z^n = k.z^n$$

where p is pressure, z in sinkage, b is width of the wheel and k_c, k_φ, k and n are soil constants.

For a rigid wheel or a high-pressure tire the sinkage can be derived from this formula and following expression found:

$$z_{max}^{n+\frac{1}{2}} = \frac{F_1}{\left(1 - \frac{n}{3}\right)\left(\frac{k_c}{b} + k_\varphi\right) b\sqrt{D}}$$

By a simple transformation we get

$$z_{max}^{n} = \frac{F_1}{b\sqrt{Dz}\; k \left(1 - \frac{n}{3}\right)} = \frac{F_1}{b\ell} \; \frac{1}{k\left(1 - \frac{n}{3}\right)}$$

$$p_{max} = \frac{1}{1 - \frac{n}{3}} \, p_{ave}$$

For a low-pressure tire $p = \frac{F_1}{b\ell}$, which gives

$$z^n = \frac{F_1}{(k_c + b\, k_\varphi)\, \ell}$$

For a low-pressure tire we further may put

$$p = p_i + p_c$$

where p_i is the inflation pressure and p_c is determined by the stiffness of the cord.

The inflation pressure can in its turn be related to the carrying capacity of the tire. An equation for this can be written in the form:

$$F_1 = A_1 D^{n_1} B^{n_2} (p_i + A_2)^{n_3}$$

where B and D are tire dimensions and A_1, A_2, n_1, n_2, n_3 are tire constants.

Traction as a function of soil values.

The gross tractive force R_4, which for a tire with lugs is essentially a function of the shear stress in the soil, can be written as (ref. 4)

$$R_4 = A (c + p \tan \phi) = A c + F_1 \tan \phi$$

(low-pressure tire, $p = F_1/b \ell$, $A = b \ell$)

The net tractive force F_2 is found by subtracting the 'rolling resistance' R_3

$$F_2 = A c + F_1 \tan \phi - R_3$$

and the coefficient of net traction f by dividing by F_1

$$f = \frac{F_2}{F_1} = \frac{c}{p} + \tan \phi - \frac{R_3}{F_1}$$

The rolling resistance of a tire can be written

$$R_3 = F + C + E$$

where F is due to tire deformation, C is due to vertical soil compaction $= \frac{b \; k}{n+1} z^{n+1}$, and E is caused by bulldozing the soil (ref. 5).

$$E = \gamma z^2 K_p^2 (b + \frac{1}{3} z \; K_p \; \Phi) \; (1 + K_p \tan \Phi')$$

The tire deformation work is in loose soil and with inflation pressures normally used of minor relative importance and can therefore be neglected here. Inserting R_3 in the formula for f and then $z = \left(\frac{p}{k}\right)^{1/n}$ and $p = \frac{F_1}{\ell b}$ we get f expressed in p and soil values.

$$f = \frac{c}{p} + \tan \phi - \left(\frac{p}{k}\right)^{\frac{1}{n}} \frac{1}{\ell(n + 1)} - \left(\frac{p}{k}\right)^{\frac{2}{n}} \frac{A_1}{\ell p} - \left(\frac{p}{k}\right)^{\frac{3}{n}} \frac{A_2}{pb\ell}$$

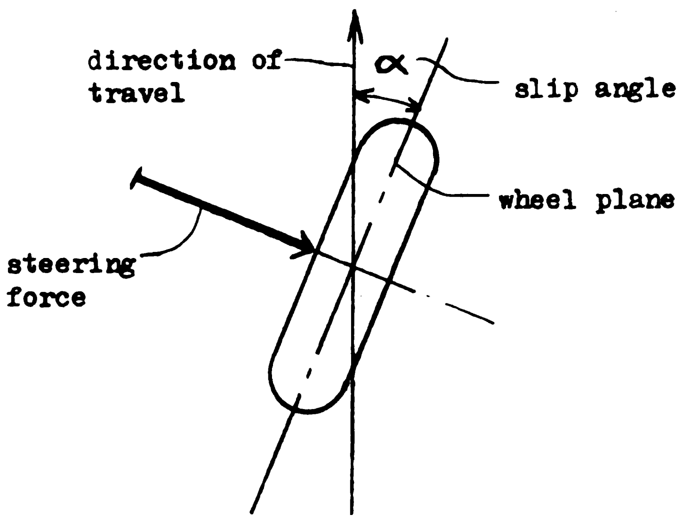
where A_1 and A_2 depend only on soil parameters.

This all shows that f decreases with increasing p.

Steering Forces on a Wheel

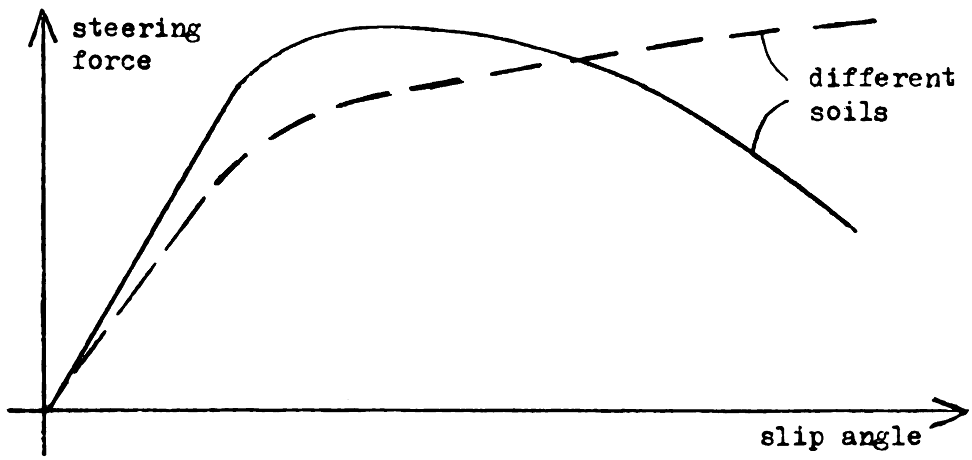
Steering forces are forces perpendicular to the wheel plane. They arise similarly as driving forces in the contact area between the wheel and the soil.

Because both the wheel and the soil generally are elastic, an angle α between the wheel plane and the direction of travel is needed in order that steering forces be produced. This angle is called the slip angle.



The slip angle causes a deflection of the tire and a deformation of the soil. The forces needed for the deformation are proportional to the deformation up to a certain value. The steering force therefore increases with the slip angle. Above a certain deformation, the shear force is almost constant. A diagram of steering force versus slip angle therefore looks like the figure below. This is basically the same relationship as for driving force versus travel reduction.

The steering force increases with an increasing load on the wheel, but the relation between these forces is probably not linear.

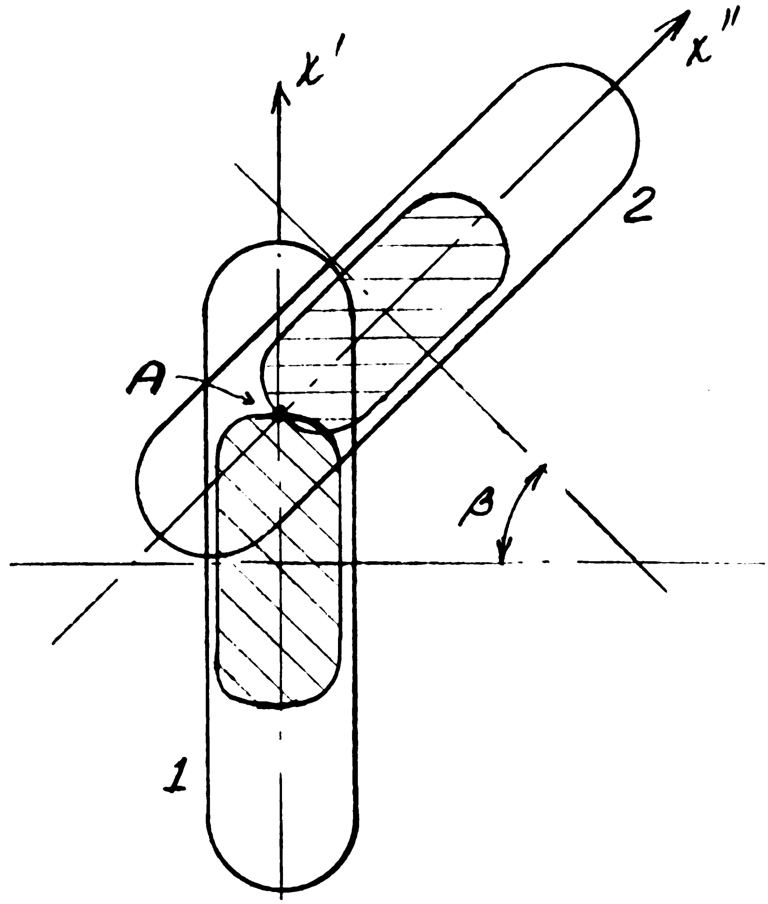


The forces discussed above are either friction or shear forces. In loose soil, there also is a bulldozing force when the wheel pushes soil in front of it.

When, besides the steering force, there is a tangential force on the wheel, the contact force between wheel and soil, which is limited by the soil strength, must be equal to the resultant of the steering force and the tangential force. Two consequences of this should be observed. When a wheel is driven with such high pull that it slips much, the steering force it can give is very low. — On soft ground, the rolling resistance can be so high that the wheel stops rolling when the steering angle exceeds a relatively low value. Then the only steering force is the bulldozing force, which is very ineffective. Theoretical considerations indicate that the slip angle where the wheel stops rolling can be as low as 35° or 40° for conditions encountered in agricultural operations.

Resistive Moment on a Steered Wheel

In order to force a wheel to roll with a radius ϱ on the ground, a steering moment around a vertical axis must be applied. This can be explained in the following way, figure below.



The shaded area is the contact area between the wheel and the ground. 1 is original position and 2 is final position of the wheel. A point of the wheel touches first ground at A and remains there till the wheel is in position 2. When an element of the tire settled at A, it had direction x', but when it leaves ground, it has been forced to assume direction x". This can have happened by the element sliding over the ground or by distortion of the tire or the soil. All this requires a moment. This resisting moment is related to the angle β between x' and x"; therefore, it increases when the length of the contact area increases and when the radius ρ decreases.

APPENDIX B. BASIC EQUATIONS OF MECHANICS FOR A POWER UNIT

System of Notations for Forces, Distances, Etc.

A system of notations will be used which was initiated by McKibben (ref. 20), has been developed by Buchele, and has been changed and extended for this study.

Positions are indicated by coordinates in the following right-handed orthogonal x-y-z system.

x-axis: When the power unit is standing still (static load) with properly inflated tires on a hard surface, the x-axis is in the surface. Positive direction forward in normal direction of travel. The x-axis is fixed in this position relative to the power unit, always at the same distance from the rear and the front axle, as long as the front wheels do not leave the ground. With changed load and correspondingly changed inflation on hard surface, the x-axis should remain tangent to the wheel circumferences. With overloaded tires on hard ground, the tires would be deflected above the x-axis; with normal load on soft ground, the tires would reach below the x-axis, due to the lesser deflection of the tires.

y-axis: Through the center of the rear wheel and positive upwards.

z-axis: In the same ground surface as used to define the x-axis. Positive to the right, when power unit is seen from behind in normal direction of travel.

x-y-plane contains the center of gravity of the power unit.

<u>Note</u>: This coordinate system is fixed relative the tractor body and does not change with the position of the wheel - soil "contact point".

<u>Units of length</u>: A non-dimensional system is used in this study with the wheelbase, i.e. the x-coordinate of the front axle, as unity.

<u>Distances</u> might be positive or negative quantities, determined by their place relative to the origin. This is necessary in order to make the equations universal.

<u>Linear speeds and accelerations</u> are positive in the positive directions of the x-axis.

<u>Angular displacements, speeds and accelerations</u> are positive in the direction determined by the right-hand rule, i.e. from the x-axis to the y-axis, etc.

<u>Forces</u>

All forces shown in pictures should be given as they act on the power unit and the implement.

Three letters will be used for forces:

W for gravity and inertia forces;

R for reaction forces from the ground;

F for other forces.

Forces and torques are in general positive in the positive directions of the axis, see above. Exceptions are forces and torques that very seldom change sign, e.g., gravity, implement resistance. These are positive in their usual direction as indicated in figure.

Dynamic conditions are treated by using d'Alembert's principle, i.e. introducing inertia forces. These inertia forces always have a direction opposite "their" acceleration and are given positive sign when the acceleration is positive. This is another exception to the general rule above.

Indices: Distances, speeds, accelerations, and forces will be given indices according to the following system:

index 0, 1,....9	quantities related to the body of the power unit (including the wheels when they are treated together with the body as a unit);
10,11,...19	quantities related exclusively to the front wheels or the front part of a power unit;
20,21,...29	quantities related exclusively to the rear wheels or the rear part of a power unit;
50,51,...59	d:o to the implement or the implements when more than one implement are treated as a unit;
60,61,...69	d:o to the "second" implement if two implements are attached and each treated separately.

The system is carried further as far as possible. So indicate e.g.:

index 0,10,20,...50...	quantities related to the mass of resp. unit, e.g.: W_0 = weight of power unit body, I_{10} = moment of inertia of front wheels;
11,21,......51...	(soil reaction) forces in the y-direction;
12,22,......52...	(soil reaction) forces in the x-direction;
13,23,......53...	(soil reaction) forces in the z-direction.

The same index should be given to the coordinates as that given to the main force in case.

In the section on forces on a wheel, the first numeral in the index is omitted.

Some Ratios

By using the dimensionless form, all distance indications are actually ratios between the actual distance and the wheel-base.

Also, for forces a non-dimensional form is wanted. Tentatively, the gravity force on the power unit, W_0, is used as power unit and the following ratios for independent variables introduced:

Implement weight ratio $i = \frac{W_{50}}{W_0}$ (B1)

Implement self-support ratio $\ell = \frac{R_{51}}{W_{50}}$ (B2)

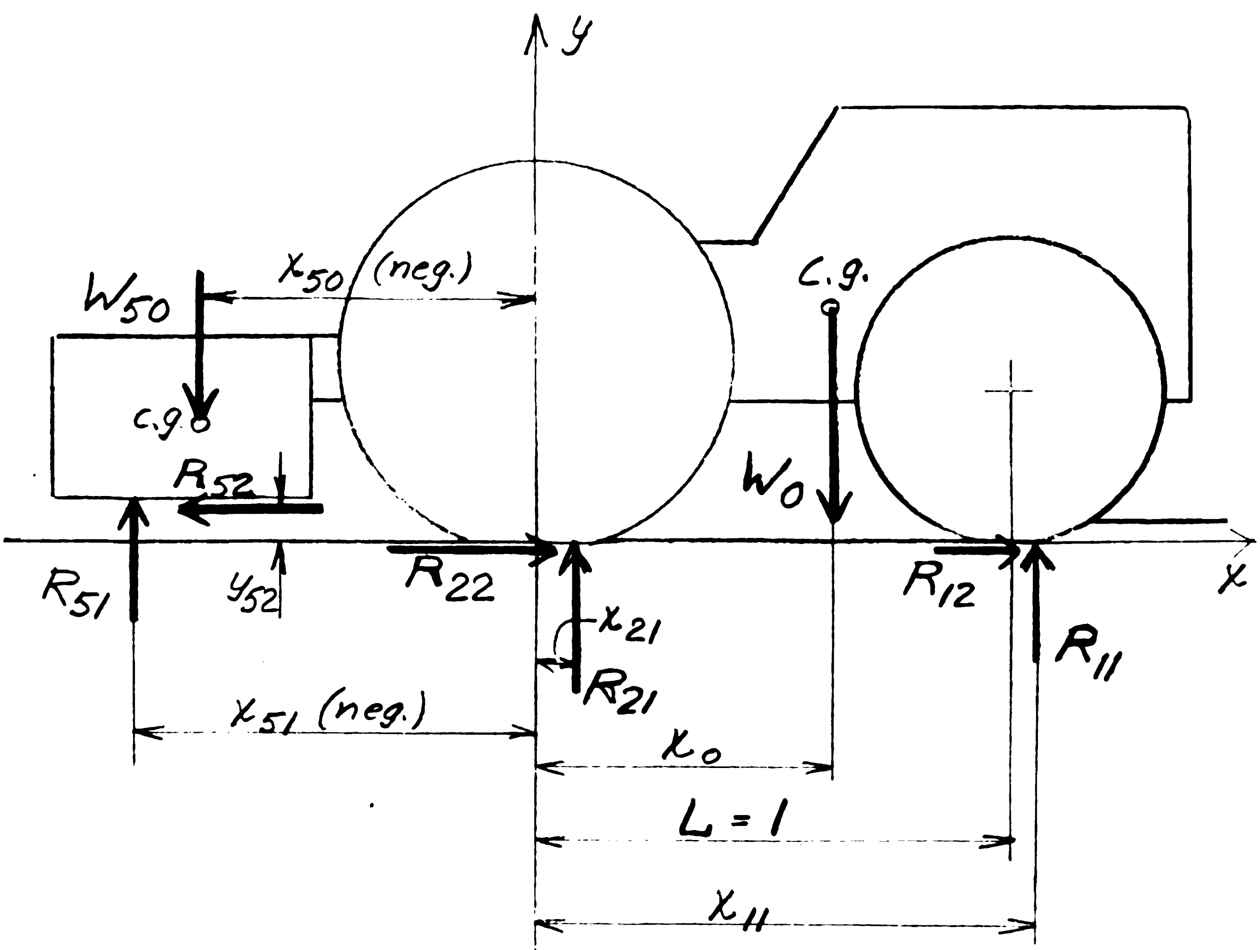
"ℓ" is = 1 for fully-trailed implements and = 0 for fully-mounted implements.

Basic Equilibrium Equations for a Power Unit and Its Implement

There are a large number of equally correct ways to write the equations of equilibrium for a power unit and its attached implement. Some ways, however, necessitate the determination of a smaller number of variables than others. This is the case when the whole machine, in this instance both the power unit and its implement, can be treated as a unity because internal forces do not then enter the equations. In a few cases, however, internal forces, e.g. drive-shaft torque, must be included, making separate treatment of the different parts of the unity necessary.

Forces in the Longitudinal Plane on a Two-axle Power Unit with Implement

The figure below shows the external forces on a two-axle power unit with implement travelling horizontally at constant speed (on horizontal ground and with equal sinkage front and rear). Air resistances are neglected on account of their usually relatively low significance (discussion on page B10).



Forces not explained earlier are:

W_0 = weight of power unit, including wheels

W_{50} = weight of implement, including load on implement

R_{51} = perpendicular forces from the ground on the implement = implement self-support

R_{52} = parallel forces from the ground on the implement = implement draft

R_{11} = perpendicular soil reaction on front wheels

R_{21} = perpendicular soil reaction on rear wheels

R_{12} = parallel soil reaction on front wheels

R_{22} = parallel soil reaction on rear wheels

Note that distances behind the rear axle or below the wheels are negative quantities. Note also the direction of forces. They are all positive as drawn.

When the baseline (x-axis) is inclined an angle β to the horizontal, the changes shown in the above figure take place.

When the power unit accelerates, inertia forces according to the following figure also enter the picture. This is the most general case and can presumably be used for any power unit plus its implements in any situation.

The equations of equilibrium are:

Sum of perpendicular forces, $\sum \uparrow = 0$;

Sum of parallel forces, $\sum \rightarrow = 0$;

Sum of moment around the origin, $\sum \circlearrowright_0 = 0$.

For the simple case in the first figure, horizontal travel at constant speed,

$$\sum \uparrow = 0 = R_{11} + R_{21} + R_{51} - W_0 - W_{50} \quad \text{(B3a)}$$

$$\sum \rightarrow = 0 = R_{12} + R_{22} - R_{52} \quad \text{(B4a)}$$

$$\sum \circlearrowright_0 = 0 = W_0x_0 + W_{50}x_{50} - R_{11}x_{11} - R_{21}x_{21} - R_{51}x_{51} - R_{52}y_{52} \quad \text{(B5a)}$$

Corresponding equations for a power unit on a slope are:

$$\sum \uparrow = 0 = R_{11} + R_{21} + R_{51} - W_0\cos\beta - W_{50}\cos\beta \quad \text{(B3b)}$$

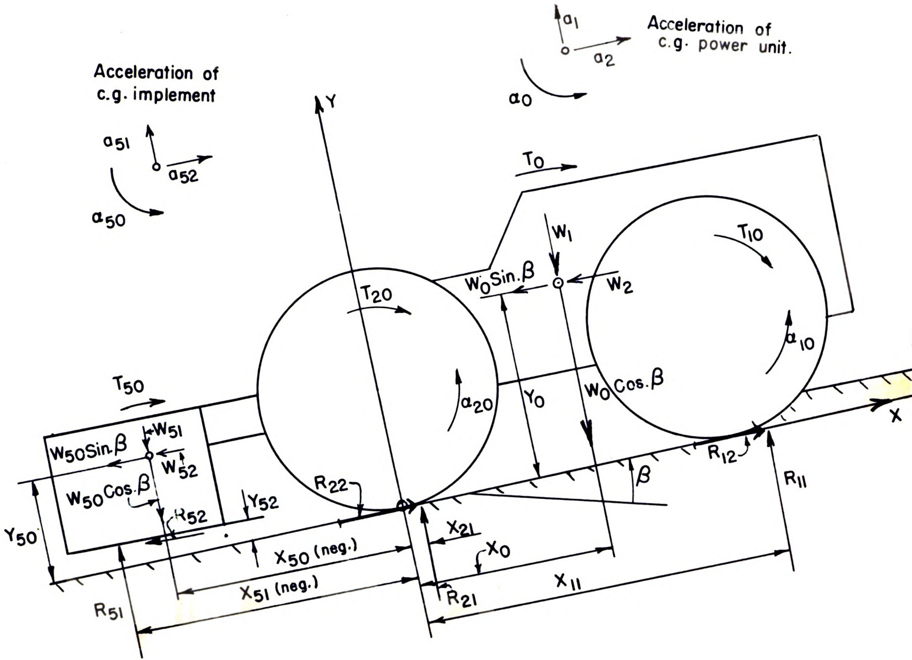
$$\sum \rightarrow = 0 = R_{12} + R_{22} - R_{52} - W_0\sin\beta - W_{50}\sin\beta \quad \text{(B4b)}$$

$$\sum \circlearrowright_0 = 0 = W_0x_0\cos\beta + W_{50}x_{50}\cos\beta - W_0y_0\sin\beta - W_{50}y_{50}\sin\beta - R_{11}x_{11} - R_{21}x_{21} - R_{51}x_{51} - R_{52}y_{52} \quad \text{(B5b)}$$

For an accelerating tractor, the equations are:

$$\sum \uparrow = 0 = R_{11} + R_{21} + R_{51} - W_0\cos\beta - W_{50}\cos\beta - W_1 - W_{51} \quad \text{(B3c)}$$

$$\sum \rightarrow = 0 = R_{12} + R_{22} - R_{52} - W_0\sin\beta - W_{50}\sin\beta - W_2 - W_{52} \quad \text{(B4c)}$$


Acceleration of
c.g. power unit.
a_1
a_2
a_0
Acceleration of
c.g. implement
a_{51}
a_{52}
a_{50}
Y
X
T_0
T_{10}
T_{20}
T_{50}
W_1
W_2
$W_0 Sin.\beta$
$W_0 Cos.\beta$
a_{10}
a_{20}
Y_0
β
R_{12}
R_{11}
R_{22}
R_{21}
X_{21}
X_0
X_{11}
X_{50} (neg.)
X_{51} (neg.)
W_{51}
W_{52}
$W_{50} Sin.\beta$
$W_{50} Cos.\beta$
R_{52}
Y_{52}
Y_{50}
R_{51}

B8

$$\Sigma \curvearrowleft = 0 = W_C x_0 \cos\beta + W_{50} x_{50} \cos\beta - W_0 y_0 \sin\beta - W_{50} y_{50} \sin\beta - R_{11} x_{11} - R_{21} x_{21} - R_{51} x_{51} - R_{52} y_{52} + W_1 x_0 + W_{51} x_{50} - W_2 y_0 - W_{52} y_{50} + T_0 + T_{10} + T_{20} + T_{50} \qquad \text{(B5c)}$$

From the definitions, pages A4 and B4, we further have:

$$R_{12} = f_1 R_{11}; \qquad \text{(B6a)}$$

$$R_{22} = f_2 R_{21}; \qquad \text{(B6b)}$$

$$W_{50} = i W_0; \qquad \text{(B7)}$$

$$R_{51} = \ell W_{50} = \ell i W_0; \qquad \text{(B8)}$$

Newton's law and d'Alembert's principle give:

$$W_1 = \frac{W_0}{g} a_1 \qquad T_0 = I_0 \alpha_0$$

$$W_2 = \frac{W_0}{g} a_2 \qquad T_{10} = I_{10} \alpha_{10}$$

$$W_{51} = \frac{W_{50}}{g} a_{51} \qquad T_{20} = I_{20} \alpha_{20}$$

$$W_{52} = \frac{W_{52}}{g} a_{52} \qquad T_{50} = I_{50} \alpha_{50}$$

(B9) (B10)

Special care needs to be taken to observe the sign of forces and distances. The following coordinates, accelerations, and forces are usually negative, as they are written in the equations: x_{50} x_{51} α_{10} α_{20} T_{10} and T_{20}. For a rear-wheel-driven tractor, R_{12} and f_1 are negative; for a front-wheel-driven, R_{22} and f_2.

The Air Resistance

The air resistance for an automobile is usually calculated according to the formula:

$$F = 0.00147\ M^2A\ \text{lb}$$

where M is the relative speed in mph,

A is the front area in sq. ft., =

= 0.8 height x width.

A tractor has probably higher coefficient of air resistance. Say:

$$F = 0.0025\ M^2A. \qquad \text{(B11)}$$

If a power unit velocity of 20 mph is assumed and a wind velocity of 25 mph, then:

$$F = 5A\ \text{lb.}$$

For a 5,000 lb. tractor frontal area might be 20 sq. ft. The wind resistance for this should be 100 lb. According to this formula, this is a maximum value which seldom occurs. For the same tractor at work with 5 mph, F = 45 lb. when working against the wind. Travelling on the road, the force with no wind might be 20 lb.

The smallest coefficient of rolling resistance is of the order of magnitude 0.02, which gives a minimum rolling resistance for this tractor of 100 lb. The air resistance is consequently always smaller than the rolling resistance and usually is considerably smaller.

Such faster moving parts as the top of the wheels have a higher resistance per area, but their area is so small that also these forces are usually very small.

Usually the accuracy of the calculations cannot be driven down to figures of this magnitude. Change in weight of fuel, in weight of dirt adhering to the power unit, etc., are usually neglected. These are of the same magnitude as the air resistance; therefore, there is no reason in most cases to include air resistance in the calculations, especially as very little is known about e.g. its line of action.

Forces in Planes, Perpendicular to the Direction of Travel.

It is sometimes not enough to know the forces on the individual wheelpairs of the power unit, but also the forces on each wheel must be known. The procedure is then first to determine the load on the wheelpairs by earlier given equations B3-10, which were found in the vertical, longitudinal plane. By similar equations, given below, the distribution of the side forces can be derived by study in the horizontal, longitudinal plane. Finally, the individual wheel forces are found by studying forces in planes, perpendicular to the direction of travel, i.e. to the x-axis. Equations, found in that way, are also given below.

The same notations as in equations B3-10 are used in this paragraph. The index ℓ means left side (negative z-values), index r, right side (positive z-values). The z-coordinate for the center of gravity of the power unit is by definition = 0.

The general purpose tractor (four-wheel tractor) as well as some four-wheel-drive tractors must be treated as two separate parts, because the joint between the front and the rear part determines the moment that can be transferred from one to the other. Because the joint is stiff in the y-direction (vertically), the power unit can be studied as one body in the horizontal, longitudinal plane, the first figure, and the separation made only when studying forces in the vertical planes (y-z planes). In this way the only force in the joint which is introduced in the equations is the moment, M, which often is = 0.

It should be noted that W_0 refers to the whole power unit, the weight of the parts being W_{10} and W_{20}, and $W_0 = W_{10} + W_{20}$.

The first figure gives (page B13):

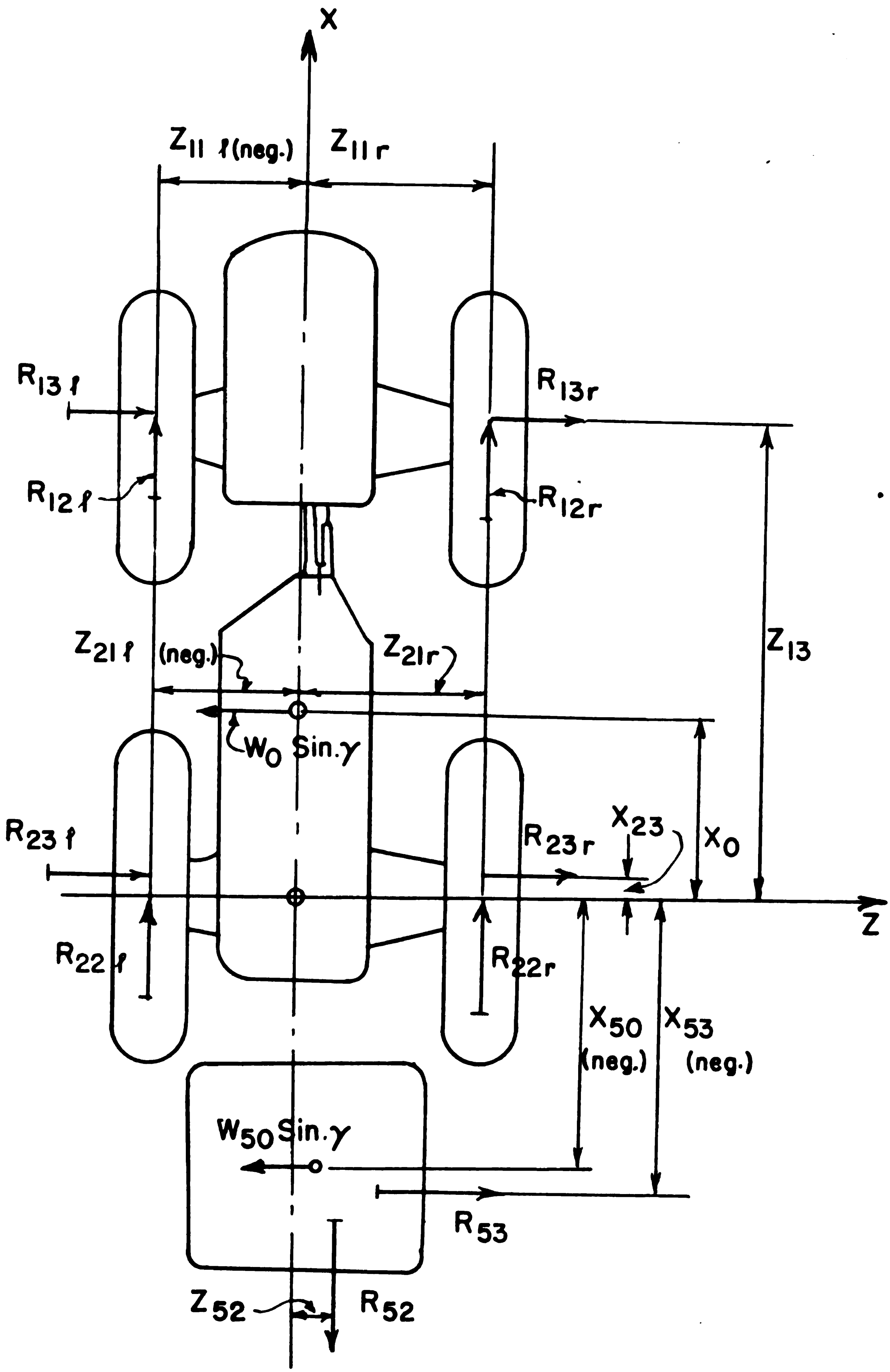
$$\sum \uparrow x : R_{12_\ell} + R_{12_r} + R_{22_\ell} + R_{22_r} - R_{52} = 0 \qquad \text{(B12a)}$$

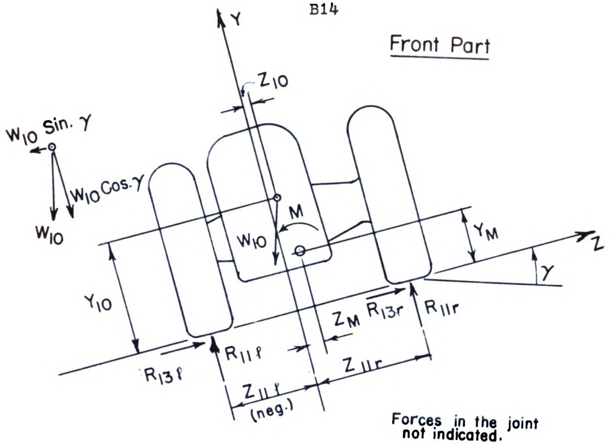
$$\sum \xrightarrow{z} : R_{13_\ell} + R_{13_r} + R_{23_\ell} + R_{23_r} + R_{53} - W_0 \sin\gamma - W_{50} \sin\gamma = 0; \qquad \text{(B13a)}$$

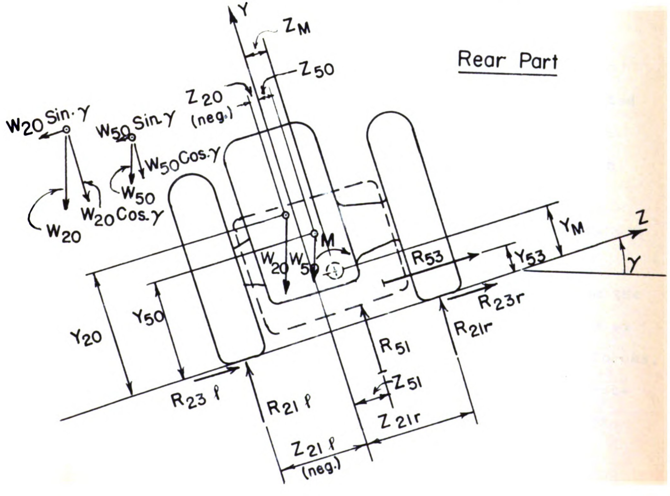
$$\sum \overset{\curvearrowright}{\underset{xz}{0}} : -R_{12_\ell} z_{11_\ell} - R_{12_r} z_{11_r} - R_{22_\ell} z_{21_\ell} - R_{22_r} z_{21_r} + R_{13_\ell} x_{13} + R_{13_r} x_{13} + R_{23_\ell} x_{23} + R_{23_r} x_{23} + R_{52} z_{52} + R_{53} x_{53} - W_0 \sin\gamma\, x_0 - W_{50} \sin\gamma\, x_{50} = 0 \qquad \text{(B14a)}$$

With only a slight change the figure on page B5 can be used to give the corresponding equations to equations B3a and B5a.

$$\sum \uparrow y : R_{11_\ell} + R_{11_r} + R_{21_\ell} + R_{21_r} + R_{51} - W_0 \cos\gamma - W_{50} \cos\gamma = 0 \qquad \text{(B15a)}$$


X
Z_{11} ℓ(neg.)
Z_{11} r
R_{13} ℓ
R_{13r}
R_{12} ℓ
R_{12r}
Z_{13}
Z_{21} ℓ
(neg.)
Z_{21r}
W_0 Sin.γ
R_{23} ℓ
R_{23r}
X_{23}
X_0
Z
R_{22} ℓ
R_{22r}
X_{50}
(neg.)
X_{53}
(neg.)
W_{50} Sin.γ
R_{53}
Z_{52}
R_{52}


Front Part
Y
Z
Z_{10}
W_{10} Sin. γ
W_{10} Cos. γ
W_{10}
M
Y_M
γ
Y_{10}
Z_M
R_{13r}
R_{11r}
R_{11l}
R_{13l}
Z_{11r}
Z_{11l} (neg.)
Forces in the joint not indicated.


Rear Part
Y
Z
Z_M
Z_{50}
Z_{20} (neg.)
W_{20} Sin. γ
W_{50} Sin. γ
W_{50} Cos. γ
W_{50}
W_{20} Cos. γ
W_{20}
M
Y_M
R_{53}
Y_{53}
γ
Y_{20}
Y_{50}
R_{23r}
R_{21r}
R_{51}
Z_{51}
R_{23l}
R_{21l}
Z_{21r}
Z_{21l} (neg.)

$$\sum \overset{\curvearrowright}{\underset{xy}{0}}: W_0 \cos\gamma\, x_0 + W_{50} \cos\gamma\, x_{50} - (R_{11_\ell} + R_{11_r}) x_{11} -$$

$$- (R_{21_\ell} + R_{21_r}) x_{21} - R_{51} x_{51} - R_{52} y_{52} = 0 \qquad \text{(B16a)}$$

In the y-z-planes we get for the front part (page B14):

$$\sum \overset{\curvearrowright}{\text{joint}}: -M - R_{11_\ell}(z_{11_\ell} - z_M) - R_{11_r}(z_{11_r} - z_M) -$$

$$- R_{13_\ell} y_M - R_{13_r} y_M + W_{10} \cos\gamma (z_{10} - z_M) -$$

$$- W_{10} \sin\gamma (y_{10} - y_M) = 0 \qquad \text{(B17a)}$$

and for the rear part:

$$\sum \overset{\curvearrowright}{\text{joint}}: M - R_{21_\ell}(z_{21_\ell} - z_M) - R_{21_r}(z_{21_r} - z_M) -$$

$$- R_{23_\ell} y_M - R_{23_r} y_M - R_{51}(z_{51} - z_M) + R_{53}(y_{53} - y_M) +$$

$$+ W_{20} \cos\gamma (z_{20} - z_M) - W_{20} \sin\gamma (y_{20} - y_M) +$$

$$+ W_{50} \cos\gamma (z_{50} - z_M) - W_{50} \sin\gamma (y_{50} - y_M) = 0 \qquad \text{(B18a)}$$

The implement here has been treated as rigidly connected to the rear part of the power unit. If there is a pivot between implement and power unit in the x-direction, equation 18a is not true. The corresponding equation must then be found in a similar manner as used for the parts of the jointed power unit.

By taking moments around the joint, we eliminate from the equation the pure forces in the joint which are not indicated in the figure and in which we are not interested. These forces, however, prohibit us from taking sums of forces in two directions for each part. Instead we get the following relationships:

$$W_0 = W_{10} + W_{20} \quad (B19)$$

$$W_0 y_0 = W_{10} Y_{10} + W_{20} y_{20} \quad (B20)$$

$$0 = W_{10} z_{10} + W_{20} z_{20} \quad (B21)$$

Further, usually M = 0.

These equations are general for a two-part power unit with rigidly mounted implements on the rear part. For the special case where the front part is just the front axle of a general purpose tractor, M = 0 and W_{10} small compared to W_0, wherefore $z_{20} = 0$. Equations B12a - 16a remain unchanged for this case but instead of equations B17a and B18a, we get for the front axle:

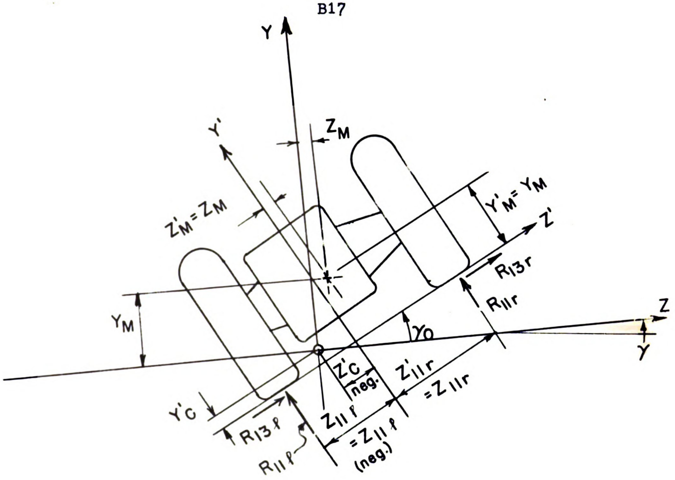
$$-R_{11_\ell}(z_{11_\ell} - z_M) - R_{11_r}(z_{11_r} - z_M) - R_{13_\ell} y_M -$$
$$-R_{13_r} y_M + W_{10}\cos\gamma(z_{10} - z_M) - W_{10}\sin\gamma(y_{10} - y_M) =$$
$$= 0 \quad (B17b)$$

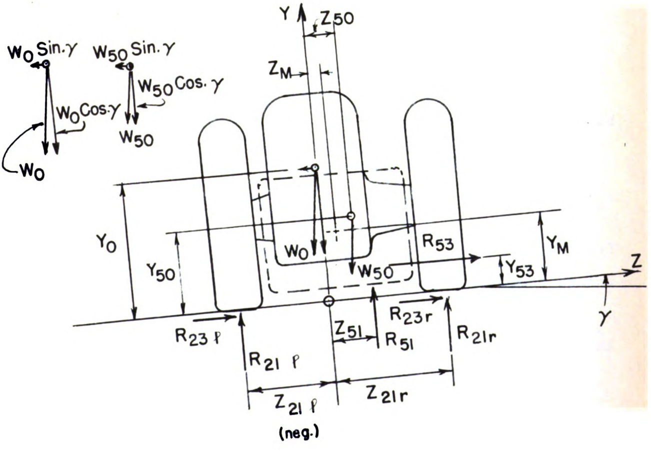
and for the rest of the tractor:

$$-R_{21_\ell}(z_{21_\ell} - z_M) - R_{21_r}(z_{21_r} - z_M) - R_{23_\ell} y_M -$$
$$-R_{23_r} y_M - R_{51})z_{51} - z_M) + R_{53}(y_{53} - y_M) -$$
$$-W_{20}\cos\gamma\, z_M - W_{20}\sin\gamma(y_{20} - y_M) + W_{50}\cos\gamma(z_{50} - z_M) -$$
$$-W_{50}\sin\gamma(y_{50} - y_M) = 0; \quad (B18b)$$

$W_{10}\cos\gamma(z_{10} - z_M)$ and $W_{10}\sin\gamma(y_{10} - y_M)$ are often small and can be neglected.

Most 'joined' tractors have a device which limits the angle between the front and the rear part of it to some value $_0$. When this has happened the power unit may again be con-


Y
Y'
Z_M
$Z'_M = Z_M$
$Y'_M = Y_M$
Z'
R_{13r}
R_{11r}
Z
Y_M
γ_0
γ
Z'_C
neg.
Z'_{11r}
$= Z_{11r}$
Y'_C
$R_{13\ell}$
$Z_{11\ell}$
$= Z_{11\ell}$
(neg.)
$R_{11\ell}$


W_0 Sin. γ
W_{50} Sin. γ
W_{50} Cos. γ
W_0 Cos. γ
W_{50}
W_0
Y
Z_{50}
Z_M
Y_0
Y_{50}
W_0
W_{50}
R_{53}
Y_M
Y_{53}
Z
γ
R_{23r}
$R_{23\ell}$
$R_{21\ell}$
Z_{51}
R_{51}
R_{21r}
$Z_{21\ell}$
Z_{21r}
(neg.)

sidered as one body and the forces and equations appear thus. (For clarity the front and rear end are pictures separately, page B17, but no inner forces are, of course, introduced.)

$$\Sigma \uparrow y: R_{11_\ell} \cos\gamma_0 + R_{11_r}\cos\gamma_0 + R_{13_\ell}\sin\gamma_0 + R_{13_r}\sin\gamma_0 + R_{21_\ell} + R_{21_r} + R_{51} - W_0\cos\gamma - W_{50}\cos\gamma = 0; \quad \text{(B15c)}$$

$$\Sigma \rightarrow z: -R_{11_\ell}\sin\gamma_0 - R_{11_r}\sin\gamma_0 + R_{13_\ell}\cos\gamma_0 + R_{13_r}\cos\gamma_0 + R_{23_\ell} + R_{23_r} + R_{53} - W_0\sin\gamma - W_{50}\sin\gamma = 0; \quad \text{(B13c)}$$

$$\Sigma \curvearrowright_0 yz: -R_{11_\ell}(z_{11_\ell} + z_c') - R_{11_r}(z_{11_r} - z_c') - R_{13_\ell} y_c' - R_{13_r} y_c' - R_{21_\ell} z_{21_\ell} - R_{21_r} z_{21_r} + R_{53} y_{53} - R_{51} z_{51} - W_0 \sin\gamma\, y_0 - W_{50}\sin\gamma\, y_{50} + W_{50}\cos\gamma\, z_{50} = 0; \quad \text{(B22c)}$$

From geometrical considerations we get:

$$y_c' = y_M(1 - \cos\gamma_0) + z_M \sin\gamma_0 \quad \text{(B23)}$$

$$z_c' = z_M(1 - \cos\gamma_0) - y_M \sin\gamma_0 \quad \text{(B24)}$$

This is an undetermined case because all forces cannot be found without further assumptions.

For a <u>tricycle type tractor</u> the equations can be found by simplifying equations B12a - 16a and B22c.

$$\Sigma \uparrow x : R_{12} + R_{22_\ell} + R_{22_r} - R_{52} = 0 \quad \text{(B12d)}$$

$$\Sigma \uparrow y : R_{11} + R_{21_\ell} + R_{21_r} + R_{51} -$$

$$- W_0 \cos\gamma - W_{50} \cos\gamma = 0 \quad \text{(B15d)}$$

$$\Sigma \xrightarrow{z} : R_{13} + R_{23_\ell} + R_{23_r} + R_{53} -$$

$$- W_0 \sin\gamma - W_{50} \sin\gamma = 0 \quad \text{(B13d)}$$

$$\Sigma \curvearrowright 0_{xz} : -R_{12} z_{11} - R_{22_\ell} z_{21_\ell} - R_{22_r} z_{21_r} +$$

$$+ R_{13} x_{13} + R_{23_\ell} x_{23} + R_{23_r} x_{23} +$$

$$+ R_{52} z_{52} + R_{53} x_{53} - W_0 \sin\gamma x_0 -$$

$$- W_{50} \sin\gamma x_{50} = 0 \quad \text{B14d)}$$

$$\Sigma \curvearrowright 0_{xy} : W_0 \cos\gamma + W_{50} \cos\gamma - R_{11} x_{11} -$$

$$- (R_{21_\ell} + R_{21_r}) x_{21} - R_{51} x_{51} - R_{52} y_{52} = 0 \quad \text{(B16d)}$$

$$\Sigma \curvearrowright 0_{yz} : -R_{11} z_{11} - R_{21_\ell} z_{21_\ell} - R_{21_r} z_{21_r} +$$

$$+ R_{53} y_{53} - R_{51} z_{51} - W_0 \sin\gamma y_0 -$$

$$- W_{50} \sin\gamma y_{50} + W_{50} \cos\gamma z_{50} = 0 \quad \text{(B22d)}$$

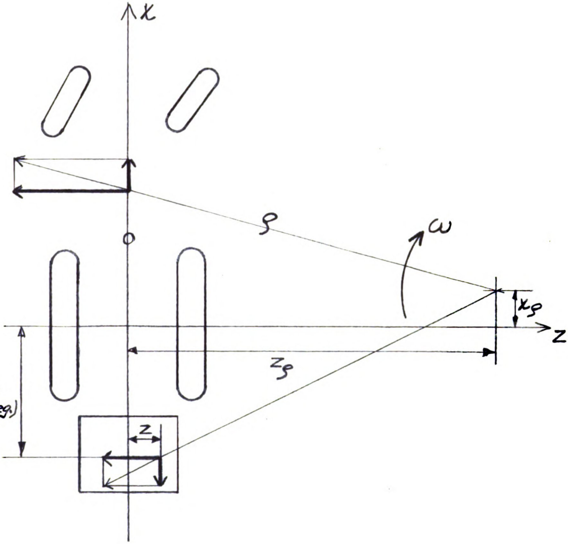
Equation B22d could also be found from equations B17b and B18b by introducing $y_M = 0$, $z_{11} = z_{11_r}$ and $W_{10} = 0$.

The equations for the individual wheel loads as given here are still more complicated than the equations for axle loads because they contain more factors. They become slightly simplified if more relationships are imposed upon them or by assumptions, but they will probably still be too clumsy to handle analytically in other cases than just to check a given design. When trying to find the best combination of all quantities involved, an analog computer seems to be the best solution here also.

The "Centrifugal" Force

There are many lateral forces on a turning tractor, but the one of main interest in connection with stability problems is the "centrifugal force". This discussion will be limited to a power unit in steady turn with the angular velocity ω and a constant radius z_ρ to the xy-plane.

It can easily be seen that the radius ρ is different for different points in the xy-plane; but also, that the component of the centrifugal acceleration in the z-direction is constant $= -z_\rho \omega^2$. The centrifugal acceleration in the z-direction for any point is therefore $= -(z_\rho - z)\omega^2$. It also can be shown that the acceleration component in the x-direction is $= (x - x_\rho)\omega^2$. The axis of rotation being in the y-direction, there is no y-component.


x
ρ
ω
0
$x_ρ$
Z
$z_ρ$
x
(neg.)
z