SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

AIR1854 REV. A

Issued 1985-03
Revised 1990-08
Reaffirmed 2013-03

Superseding AIR1854

Battery Powered Aircraft Tow Tractors - Factors for Design Consideration

RATIONALE

AIR1854A has been reaffirmed to comply with the SAE five-year review policy.

TABLE OF CONTENTS

1. SCOPE:

This SAE Aerospace Information Report (AIR) identifies and summarizes the various factors that must be considered and evaluated by the design or specifying engineer in establishing the specifications and design characteristics of battery-powered aircraft tow tractors.

This AIR is presented in two parts. The first part is simply a summarization of design factors that must be considered in establishing vehicle specifications and design characteristics. The second part refers particularly to the performance characteristics of an aircraft tow tractor. Some definitions, formulas, data, and an example are provided mainly for assisting the specifying engineers of potential buyers and users of aircraft tow tractors in the evaluation and comparison of their requirements with the performance capabilities of the various tow tractors offered by the tow tractor manufacturers. Although the design engineers could also use the formulas and data in their calculations of the performance specifications of aircraft tow tractors, this AIR is not intended to provide the methods and all data necessary for detailed calculations and design of a battery-powered aircraft tow tractor.

2. REFERENCE DOCUMENTS:

ARP1247	General Requirements for Aerospace Ground Support Equipment, Motorized and Nonmotorized
AIR1363	Four Wheel Drive Aircraft Tow Tractors - Factors for Design Consideration
AS1614	Commercial Aircraft Towbar Attach Fitting Interface
ARP1816	Charger For Battery Powered Ground Support Equipment
ARP1817	Battery Industrial, Lead Acid Type For Use in Electric Powered Ground Support Equipment
ARP1892	Electrical Connectors For Use in Battery Powered Ground Support Equipment

3. DESIGN FACTORS:

The following factors must be considered and evaluated in establishing aircraft tow tractor specifications and design:

3.1 Aircraft Characteristics:

a. Dimensions

b. Number of landing gears and wheels

c. Attachment point for towing

d. Gross weight, empty weight, and weight distribution on the landing gears

3.1 (Continued):

e. Coefficient of breakaway resistance of the aircraft (as a percentage of aircraft weight) for initial motion directed

1. Straight ahead

2. In a turn

f. Coefficient of rolling resistance of the aircraft (as a percentage of aircraft weight) for constant motion on various horizontal surfaces

g. Turning radius of the aircraft

h. Angular steering limitation of the aircraft tow fitting

i. Towing load limitations of the aircraft tow fitting at different directions of towing or pushing

j. Amount of thrust of engines at idle

The aircraft characteristics are normally provided by the aircraft manufacturer in the Facilities Planning Manual of each particular model of aircraft. The design or specifying engineer must consider all models of aircraft which are to be handled by the tow tractor.

3.2 Airport Conditions:

a. Maximum grades to be negotiated

b. Minimum speeds required for crossing active taxiways and runways

c. Parking requirements:

1. Parallel or nose-in at gates

2. Spacing from other aircraft

3. Proximity to other fixed physical features

4. Need for remote parking

d. Paving strength of ramps, taxiways, runways, and access roads

e. Road clearance and bridge and overpass limitations

f. Maximum approach and breakover angles to be negotiated on ramps, taxiways, runways, and access roads

g. Other towing equipment limitations, physical or regulatory, unique to the local situation

3.2 (Continued):

h. Anticipated towing distances and routes between aircraft maintenance and storage areas and cargo and passenger terminals, etc.

i. Anticipated daily push-out frequencies and distances by type (weight) of aircraft

j. Availability of battery charging facilities

k. Location of battery chargers

l. Environmental factors and airport surface conditions:

1. Temperature

2. Humidity

3. Altitude

4. Rain

5. Snow or ice

6. Material and condition of airport surface when dry

7. Oil, hydraulic fluid, deicing fluid on airport surface

8. Other pollutants on airport surface

The airport conditions are specified usually by the airlines, ground handling company or airport authorities user of the tow tractor.

3.3 Tow Vehicle - General Characteristics:

a. Dimensional limitations

b. Visibility requirements

c. Operator’s compartment location(s)

d. Speed requirements:

1. Maximum speed-tractor only on level surface

2. Maximum towing speed-tractor and towed aircraft with maximum weight on level surface

3.3 (Continued):

e. Braking capability:

1. Minimum stopping distance at maximum speed - tractor only (or maximum deceleration)

2. Minimum stopping distance at maximum towing speed - tractor and towed aircraft (or maximum deceleration)

3. Emergency braking capability

f. Maneuverability requirements and steering capability:

1. Front-wheel steering

2. Four-wheel coordinated steering

3. Two-mode steering: front-wheel and four-wheel coordinated

4. Two-mode steering: four-wheel coordinated and four-wheel crab

5. Three-mode steering: front-wheel, four-wheel coordinated and four-wheel crab

6. Four-mode steering: front-wheel, rear-wheel, four-wheel coordinated and four-wheel crab

7. Emergency steering capability

g. Power Train-special requirements about the major components (motor(s), reducer(s), axles, wheels, and tires)

h. Maintenance requirements and service accessibility

i. Requirements for integral electrical power equipment to support the aircraft systems during towing and standby operations

j. Method of attachment to the aircraft (e.g., type and location of the tow hitches)

k. Requirements for ground control communications, including communications between the tow tractor and aircraft

l. Vehicle lights

3.3 (Continued):

m. Human factor requirements:

1. Environmental protection of operator and passenger(s) (cab)

2. Comfort-location and type of operator's seat, location of controls and instruments, heating and ventilation, operator's compartment lighting, noise level, etc.

3. Safety-access to and from operator's compartment or cab, steps, doors, warning lights and beepers, windshield washer and wipers, visibility to front and rear hitch areas, fire protection, etc.

n. Special requirements imposed by airport authorities and regulations

o. Special requirements imposed by the tractor user or buyer

The general characteristics of a tow tractor shall be determined so that the vehicle would be able to meet the requirements imposed by the characteristics of the different models of aircraft which will be towed and by the airport conditions where the tractor will operate, providing efficient, safe, and comfortable operation and maintenance.

3.4 Tow Vehicle - Electrical Characteristics:

a. Battery characteristics and battery related factors (see ARP1817):

1. Type: flat plate, tubular plate, lead acid, etc.

2. Voltage

3. Capacity

4. Access for service, watering, changing

5. Removal and installation provisions

6. Battery layout

7. Battery location and weight distribution

b. Type of charger and charger control characteristics (see ARP1816)

c. Type connectors (see ARP1892)

3.4 (Continued):

d. Type of drive motor(s) controller:

1. Vehicle acceleration control
2. Vehicle forward-reverse motion control

e. Motor overspeed protection for severe grades

f. Accessory electric power source:

1. Converter
2. Battery
3. Voltage

g. Safety devices-seat switches, emergency battery disconnect, driveaway interlock, etc.

h. Waterproofing requirements

i. Fire suppression requirements

4. PERFORMANCE:

4.1 General Notes:

During a towing operation an aircraft tow tractor must be able to overcome all forces resisting the motion of the tow tractor-aircraft train. The power train of the tow vehicle must be able to produce a tractive effort between the tires and airport surface equal to the maximum total resistance, i.e., the maximum amount of all forces resisting the motion of the tractor and aircraft. Since the tractive effort is proportional to the torque on the drive wheels shaft, the power train of the vehicle must be able to develop the torque required to produce the needed tractive effort. The power train of the tow tractor must also be able to develop enough power to accelerate the tow tractor alone to the specified maximum speed and the tractor-aircraft train to the specified maximum towing speed. On the other hand, the maximum tractive effort that can be developed between the tires and the ground surface is proportional to the weight over the drive wheels. Therefore, a tow tractor must have adequate weight and weight distribution to provide the required maximum tractive effort at specified airport surface conditions.

4.1 (Continued):

The braking system of a tow tractor must be able to develop adequate braking force between the vehicle tires and the road surface for a safe braking of the tractor, as well as for a safe braking of the tractor and aircraft. Normally during a towing operation only the braking system of the tow tractor is used for braking tow tractor-aircraft train. However, in case of emergency during towing the tow tractor-aircraft train may be stopped by the aircraft brakes being applied by the captain or braking mechanic of the aircraft. The maximum braking force that can be developed by a tow tractor is proportional to the weight of the tractor. Therefore, the weight of the tractor imposes the major limitations of its braking capability.

The following equations are correct with sufficient approximation at the assumption that an aircraft tow tractor is a relatively heavy, slow-moving, low profile ground vehicle operating on surfaces with not more than 10% grade. However, it is highly recommended that the specifying or design engineer verify any data and use correct equations depending on the specific type and application of the tow tractor.

For example, the resistance of motion produced by the air is not discussed and included in the provided equations for the total resistance, since at low speeds the air resistance is insignificant. However, if the tow tractor moves against strong wind, a significant air resistance is added to all other forces opposing the motion, therefore this additional resistance must be considered in the performance calculations.

In this discussion the weight of the tow vehicle is considered as being equally distributed on the four wheels. For simplicity, the effect of the load transfer, due to the drawbar pull and to the inertial forces during acceleration or deceleration, is neglected as insignificant in establishing the major performance specifications. However, in the detailed calculations and design of the drive system and braking system of the vehicle, the load transfer is one of the major factors for design consideration.

4.2 Resisting Forces:

a. Acceleration Resistance (AR): This is the inertial resistance of the mass of a vehicle to a change in vehicle speed.

The force required to accelerate a vehicle on a level surface from a lower speed to a higher speed is equal to the acceleration resistance of the vehicle.

The tow tractor must overcome the acceleration resistance of the tow tractor-aircraft train. This resistance can be calculated by the following formula:

$$AR = \frac{(WA + WT)\ a}{g} \qquad \text{(Eq.1)}$$

4.2 (Continued):

where:

WA = Weight of aircraft
WT = Weight of tow tractor
a = Acceleration of tow tractor-aircraft train
g = Acceleration of gravity (gravitational constant)

In US Customary Units g = 32.2 ft/s^2

In SI Units g = 9.81 m/s^2

An acceleration of a = 0.015 g is usually accepted as reasonable considering the limitation of the impact load on the nose gear of the aircraft. At this condition the acceleration resistance is as follows:

$$AR = 0.015\ (WA + WT) \qquad \text{(Eq.2)}$$

b. Rolling Resistance (RR): This is a dynamic resistance of the motion resulting from the following:

1. The friction between the tires of a vehicle and the surface on which they roll
2. Deformation of the tires and ground surface
3. Friction in the vehicle wheel bearings

The force required to move a vehicle on a level surface with a constant speed is equal to the rolling resistance of the vehicle.

The tow tractor must overcome the rolling resistance of the tow tractor-aircraft train. This resistance can be calculated by the following formula:

$$RR = f\ (WA + WT) \qquad \text{(Eq.3)}$$

where:

f = Coefficient of rolling resistance

Based on empirical tests, various coefficients of rolling resistance have been established. Usually the coefficient of rolling resistance is expressed in percent as follows in Table 1:

TABLE 1

Surface Type	f% Dry Surface	f% Wet Surface
Hard asphalt	1.4	1.8
Concrete road	1.8	2.2
Snow and ice	2.0	2.5
Snow (hard packed)	2.5	3.1
Snow (soft)	3.3	4.1

4.2 (Continued):

Under normal conditions, the coefficient of rolling resistance of an aircraft is usually considered to be 1 to 2% in a straight pull or push and 2 to 4% in a turning maneuver. An average of f = 2% is considered reasonable for the preliminary calculation of the rolling resistance. Usually the coefficient of rolling resistance of the tow tractor is accepted to be the same as the coefficient of rolling resistance of the aircraft. Equation 3 is correct at this assumption. At an average f = 2%, the rolling resistance is as follows:

$$RR = 0.02\,(WA + WT) \qquad \text{(Eq.4)}$$

c. Grade Resistance (GR): This is the components of the vehicle weight acting against the motion when the vehicle moves up a grade.

The tow tractor must overcome the grade resistance of tow tractor-aircraft train when towing an aircraft up a slope. This resisting force can be approximated by the following formula:

$$GR = G\,(WA + WT) \qquad \text{(Eq.5)}$$

where:

G = Grade in percent (ratio of the vertical rise to the horizontal projection of the distance between two points of the ground surface in percent)

An average of 2% grade of the airport surface is considered reasonable for general calculations of the grade resistance. At such assumption, the grade resistance is as follows:

$$GR = 0.02\,(WA + WT) \qquad \text{(Eq.6)}$$

4.2 (Continued):

d. Engine Thrust (ET): The thrust produced by the idling aircraft engines is an important consideration in determining the major specifications of an aircraft tow tractor. When the tow tractor moves an aircraft against the thrust of the aircraft engines, this thrust is added to the other forces resisting the motion of the aircraft and must be overcome by the tow tractor. The total engine thrust will vary with the type and number of running aircraft engines. However, engine idle thrust data is provided by the engine manufacturers and the number of engines started prior to push-out operations, if any, is specified by the user of the tractor in accordance with the individual operating procedures.

e. Breakaway Resistance (BR): This is the sum of the acceleration and rolling resistances of a vehicle that must be overcome for starting the motion of the vehicle. The highest value of static resistance to motion occurs at that point at which motion is impending. Therefore, at the point of impending motion the combined value of the acceleration and rolling resistances is higher than it is after motion has been initiated.

The tow tractor must overcome the breakaway resistance of tow tractor-aircraft train for starting to tow the aircraft. This resistance can be calculated by the following formula:

$$BR = f_B\,(WA + WT) \qquad \text{(Eq.7)}$$

where:

f_B = Coefficient of breakaway resistance

Under normal conditions, the average coefficient of breakaway resistance of an aircraft in a straight pull or push is 4%. Usually the same coefficient of breakaway resistance is accepted for the tow tractor. Equation 7 is correct at this assumption. At an average f_B = 4%, the breakaway resistance is as follows:

$$BR = 0.04\,(WA + WT) \qquad \text{(Eq.8)}$$

NOTE: The value for f_B can approach 8% in a turn.

f. Total Resistance (TR): This is the sum of all forces resisting the motion of a vehicle.

The tow-tractor must overcome the total resistance of tow tractor-aircraft train. The total resistance can be calculated by the following equations:

1. At breakaway (TR_B):

$$TR_B = BR + GR + ET \qquad \text{(Eq.9)}$$

or:

$$TR_B = (f_B + G)(WA + WT) + ET \qquad \text{(Eq.10)}$$

4.2 (Continued):

If the accepted average values of f_B = 4% and G = 2% are used:

$$TR_B = 0.06\ (WA + WT) + ET \qquad \text{(Eq.11)}$$

2. At motion (TR_M):

$$TR_M = AR + RR + GR + ET \qquad \text{(Eq.12)}$$

or:

$$TR_M = \left(\frac{a}{g} + f + G\right)(WA + WT) + ET \qquad \text{(Eq.13)}$$

If the usually accepted values of a = 0.015 g, f = 2% and G = 2% are used:

$$TR_M = 0.055\ (WA + WT) + ET \qquad \text{(Eq.14)}$$

It is obvious that, depending on the particular conditions of operation, some of the resisting forces may not exist in the equations for the total resistance TR. For examples:

1. If no engine is idling during a towing operation ET = 0
2. If the towing is on a level surface G = 0 and GR = 0
3. If the towing is with constant velocity a = 0 and AR = 0, etc.

However, the breakaway resistance BR is always present at breakaway, and the rolling resistance RR is always present at motion of a vehicle, therefore, in a sense, they are the most important of the resisting forces.

Since each of the Equations 1 to 14 presents in fact a sum of the respective resistances of the aircraft and tow tractor, these equations can be modified and used for calculating the resisting forces of the aircraft or the resisting forces of the tow tractor as follows:

1. To calculate the resistances of aircraft consider WT = 0 and omit it in the equations.
2. To calculate the resistances of tow tractor consider WA = 0 and ET = 0 and omit them in the equations.

4.3 Major Performance Characteristics:

a. Tractive Effort (TE): This is the force that the power train of a vehicle develops between the tires of drive wheels and ground surface in direction of motion for moving the vehicle.

For starting a towing operation, a tow tractor must be able to develop a tractive effort equal to the total resistance of tow tractor-aircraft train at breakaway. The required tractive effort can be determined by the following formula:

$$TE = (f_B + G)(WA + WT) + ET \quad \text{(Eq.15)}$$

If the coefficients f_B and G for the worst condition of application of the tow tractor are used in Equation 15, the maximum required tractive effort can be calculated.

On the other hand, the maximum tractive effort that can be developed between the tires and the ground without slipping the tires is proportional to the tractor weight:

$$TE = u \times WT \quad \text{(Eq.16)}$$

where:

u = Coefficient of traction (or coefficient of road adhesion)

The coefficient of traction is a series of constants for varying road surface conditions. These constants are normally tabulated as follows in Table 2:

TABLE 2

Road Surface	u(ATA)	u(SAE)
Glaze ice	0.10	-
Hard snow	-	0.20
Oily concrete	-	0.40
Wet asphalt	0.40 - 0.60	0.40
Wet concrete	-	0.50
Dry asphalt	-	0.80
Dry concrete	0.80	0.80

Since the traction depends not only on the road surface conditions but also on the tires, different coefficient of traction is recommended by different sources for the same road surface conditions. However, a maximum of u = 0.80 and an average of u = 0.45 is used usually for tow tractor calculations.

4.3 (Continued):

b. Weight (WT): From Equations 15 and 16 the required weight of the tow tractor (WT) can be calculated:

$$WT = \frac{(f_B + G)\ WA + ET}{u - f_B - G} \qquad \text{(Eq.17)}$$

Equations 16 and 17 are correct for four-wheel drive tow tractors with equal front/rear weight distribution.

For a two-wheel drive tractor, the maximum tractive effort is limited by the weight on the drive wheels. If the weight on the drive wheels (WT_d) is expressed as part of the tractor weight (WT) by the formula:

$$WT_d = d \times WT \qquad \text{(Eq.18)}$$

where:

d is the part of the tractor weight distributed on the drive wheels, then the weight of a two-wheel drive tractor can be calculated by the following formula:

$$WT = \frac{(f_B + G)\ WA + ET}{ud - f_B - G} \qquad \text{(Eq.19)}$$

c. Drawbar Pull (DBP): This is the force with which a towing vehicle pulls or pushes another vehicle. The maximum drawbar pull that a tractor can develop illustrates the towing capabilities of the vehicle and is considered the major characteristic of the tow tractor.

The drawbar pull is equal to the total resistance of motion of the aircraft and can be calculated by the following formulas:

1. At breakaway:

$$DBP_B = (f_B + G)\ WA + ET \qquad \text{(Eq.20)}$$

2. At motion:

$$DBP_M = \left(\frac{a}{g} + f + G\right) WA + ET \qquad \text{(Eq.21)}$$

4.3 (Continued):

From Equations 17 and 20 follows another equation for determination of required weight of a tow tractor:

$$WT = \frac{DBP_B}{u - f_B - G} \qquad \text{(Eq.22)}$$

Usually the aircraft tow tractor manufacturers show in the tractors' specifications the maximum drawbar pull that the tractor is able to develop at breakaway at a maximum coefficient of traction u = 0.80.

d. Power (P): The required power that the drive motor(s) of a vehicle must develop to move the vehicle with given speed is proportional to the total resistance of motion. This is the net power delivered from the motor(s) to the vehicle drivetrain.

The required power of the drive motor(s) of a tow tractor can be calculated by the following formulas:

1. In US customary units [hp (SAE)]:

$$P = \frac{TR_M \times V}{375e_D} \text{ hp (SAE)} \qquad \text{(Eq.23)}$$

where:

TR_M = Total resistance of tow tractor-aircraft train in lbf (pounds force)
V = Speed in mph (miles per hour)
e_D = Efficiency of drivetrain

2. In SI Units (kW):

$$P = \frac{TR_M \times V}{3.6e_D} \text{ kW} \qquad \text{(Eq.24)}$$

where:

TR_M = Total resistance of tow tractor-aircraft train in kN (kilonewtons)
V = Speed in km/h (kilometers per hour)
e_D = Efficiency of drivetrain

For mechanical drivetrains, an average of e = 0.85 is usually accepted in the preliminary calculations.

4.3 (Continued):

NOTE: Equations 1 to 22 can be used for calculations in US Customary Units or in SI Units. For example, if the weight of the tractor WT, the weight of the aircraft WA, and the engine thrust ET, are in lbf (pound force), then all resistances, tractive effort, and drawbar pull will also be in lbf. If the weights of the tractor and aircraft and the engine thrust are in kN (kilonewtons) then all resistances, tractive effort, and drawbar pull will also be in kN. However, the application of the equations in both systems of units (US and SI) is illustrated in the example (see 4.6).

4.4 Capacity of the Battery (CB):

One of the major considerations in the application of a battery-powered vehicle is the limited energy capacity of the electric battery. After the battery is discharged it has to be charged while in the vehicle or exchanged with another fresh battery. Normally, the batteries of the aircraft towing tractors are not changed but are charged on the vehicle. Usually a battery-powered tow tractor is in operation (use) for 16 hours and then the tractor is out of operation for 8 hours during the charging of its battery. However, the frequency of charging depends on the duty cycle of the vehicle at the real conditions of operation. In many cases also an opportunity charging of the battery is applied between the towing application for improving overall energy capacity between the normal battery charging cycles. If the duty cycle of the tractor is known and the frequency of battery charging is specified, the required capacity of the battery could be calculated with sufficient approximation.

The major portion of the electric energy stored in the battery is used for powering the drivetrain of the vehicle, i.e., for producing mechanical work in moving the tractor and the tractor-aircraft train, plus the losses of energy in the drivetrain of the tractor. However, for determining the total battery capacity, the energy needed for powering the other systems of the tow tractor (steering, braking, heating, lighting, etc.) and the losses in the electrical system (conductors) must be added to the energy necessary for powering the drive system of the vehicle.

The battery capacity in kWh can be expressed by the formula:

$$CB = E_D + E_O + \Delta E \text{ kWh} \qquad \text{(Eq.25)}$$

where:

E_D = Energy for the drive system in kWh
E_O = Energy for the other systems in kWh
ΔE = Energy losses in electrical system in kWh

4.4 (Continued):

For preliminary calculations, the sum $E_O + \Delta E$ can be accepted as equal to 10% of the energy for drive system E_D. At this assumption the equation for the required battery capacity is as follows:

$$CB = 1.1\ E_D \tag{Eq.26}$$

Since the energy necessary for the drive system of a vehicle is proportional to the mechanical work that the vehicle produces, it is apparent that the total resistance of motion (TR_M) and the distance of travel(s) must be known (calculated), because the mechanical work is the product of both quantities (force by distance).

For calculating the mechanical work during a complete tow or push-out operation, this operation may be regarded as a sum of several elementary operations (phases) during each of which the total resistance of motion (TR_M) is constant. At this assumption, the energy for powering the drive system of the tractor can be calculated by the following equations:

In SI Units:

$$E_D = \frac{N \sum_{i=1}^{n} (TR_{Mi} \times S_i)}{2655248\ (e_M \times e_D)}\ \text{kWh} \tag{Eq.27}$$

where:

- N = Number of complete operations between battery charging cycles
- i = Index of each elementary operation
- n = Number of elementary operations
- TR_{Mi} = Average Total Resistance during the "i" elementary operation in lbf
- S_i = Distance of travel during the "i" elementary operation in ft
- e_M = Efficiency of drive motor(s)
- e_D = Efficiency of drivetrain

4.4 (Continued):

In SI Units:

$$E_D = \frac{N \sum_{i=1}^{n} (TR_{Mi} \times S_i)}{3600\ (e_M \times e_D)}\ \text{kWh} \qquad \text{(Eq.28)}$$

where:

- N = Number of complete operations between battery charging cycles
- i = Index of each elementary operation
- n = Number of elementary operations
- TR_{Mi} = Average Total Resistance during the "i" elementary operation in kN
- S_i = Distance of travel during the "i" elementary operation in m
- e_M = Efficiency of drive motor(s)
- e_D = Efficiency of drivetrain

If the expressions for E_D from Equations 27 and 28 are substituted in Equation 26, the required capacity of the battery can be determined by the following equations:

In US Units:

$$CB = \frac{N \sum_{i=1}^{n} (TR_{Mi} \times S_i)}{2413862\ (e_M \times e_D)}\ \text{kWh} \qquad \text{(Eq.29)}$$

where:

TR_{Mi} are in lbf and S_i are in ft

In SI Units:

$$CB = \frac{N \sum_{i=1}^{n} (TR_{Mi} \times S_i)}{3273\ (e_M \times e_D)}\ \text{kWh} \qquad \text{(Eq.30)}$$

where:

TR_{Mi} are in kN and S_i are in m

4.4 (Continued):

For example, a complete tow or push-out operation can be divided in the following elementary operations during each of which the Total Resistance of Motion (TR_M) is considered constant for simplification of the calculations:

(1) From the beginning of the tow or push-out operation to the point where the tow tractor-aircraft train has developed the specified maximum tow speed. The acceleration during this part of the operation can be accepted as constant and equal to one half of the specified maximum acceleration, although in reality it varies from a maximum value to zero. However, at this assumption the total resistance during the first elementary operation is as follows:

$$TR_{M1} = \left(\frac{a}{g} + f + G\right)(WA + WT) + E \quad \text{(Eq.31)}$$

where:

$a = 0.5a_{max}$

If the maximum acceleration is $a_{max} = 0.015$ g (see 4.2a), the average acceleration will be $a = 0.0075$ g.

At this assumption, the total resistance is:

$$TR_{M1} = (0.0075 + f + G)(WA + WT) + ET \quad \text{(Eq.32)}$$

The distance to travel during the first elementary operation S_i can be determined by the following equations:

In US Units:

$$S_1 = \frac{1.0756v^2}{a}\ \text{ft} \quad \text{(Eq.33)}$$

where:

v = Maximum tow speed in mph
a = Average acceleration in ft/s^2

In SI Units:

$$S_1 = \frac{0.0386v^2}{a}\ \text{m} \quad \text{(Eq.34)}$$

where:

v = Maximum tow speed in km/h
a = Average acceleration in m/s^2

4.4 (Continued):

(2) From the point where the tow tractor-aircraft train has reached the specified maximum tow speed to the end of the tow or push-out distance. During this part of the operation it may be considered that the tow tractor-aircraft train moves with a constant speed (a = o). At this assumption, the total resistance during the second elementary operation is as follows:

$$TR_{M2} = (f + G)(WA + WT) + ET \qquad \text{(Eq.35)}$$

The distance of travel during the second elementary operation S_2 can be calculated by the following:

$$S_2 = S_T - S_1 \qquad \text{(Eq.36)}$$

where:

S_T = Distance of towing (pushing)

(3) From the point where the tow tractor is disconnected from the aircraft and start moving to the point where the tractor has developed the specified maximum speed. The acceleration can be accepted as constant and equal to one half of the specified maximum acceleration [see (1)]. Then the total resistance during the third elementary operation is as follows:

$$TR_{M3} = (0.0075 + f + G)\ WT \qquad \text{(Eq.37)}$$

The distance of travel during the third elementary operation S_3 can be determined by the following formulas:

In US Units:

$$S_3 = \frac{1.0756v^2}{a}\ \text{ft} \qquad \text{(Eq.38)}$$

where:

v = Maximum tractor speed in mph
a = Average acceleration in ft/s^2

In SI Units:

$$S_3 = \frac{0.0386v^2}{a}\ \text{m} \qquad \text{(Eq.39)}$$

where:

v = Maximum tractor speed in km/h
a = Average acceleration in m/s^2

4.4 (Continued):

(4) From the point where the tow tractor has reached the specified maximum speed to the end of the complete tow or push-out operation. During the last phase of the operation it may be considered that the tractor moves with a constant speed (a = o). Also, for simplification of the calculations it may be considered that the tractor moves on a level surface (G = 0), since overall during a duty cycle the vehicle will travel the same distances uphill and downhill. At these assumptions the total resistance during the fourth elementary operation is as follows:

$$TR_{M4} = f \times WT \qquad \text{(Eq.40)}$$

The distance of travel during the fourth elementary operation S_4 can be calculated by the following formula:

$$S_4 = S_R - S_3 \qquad \text{(Eq.41)}$$

where:

S_R = Distance of travel of the tractor after the towing or push-out of the aircraft (return travel)

4.5 Braking:

Usually, the minimum stopping distance of the tow tractor itself from the maximum speed is specified as a major requirement about the braking capability of the vehicle. The stopping distance is in an inverse proportion with the deceleration. However, a deceleration of more than 0.5 g = 16.1 ft/s^2 = 4.9 m/s^2 at a panic stop is not recommended for an aircraft tow tractor. The brakes of the tractor must be able to produce the required braking force for reducing the speed of the tractor with the specified maximum deceleration. However, during a normal braking operation significantly lower values of deceleration are in effect.

For a smooth and safe braking of the aircraft, the braking system of the tow tractor must provide gradual smooth application of the brakes. If the wheels of the tractor are locked by the brakes, the tractor will skid. In such an event, usually directional control is lost with all following consequences. The situation is very aggravated because the tractor is connected to the aircraft by a towbar. The worst conditions are during braking in a turn.

4.6 Example:

It is desired to specify the major performance characteristics [drawbar pull, weight and power of drive motor(s)] and capacity of the battery of a four-wheel drive battery-powered tow tractor pushing against the idle thrust of aircraft engines, at the following aircraft and airport characteristics, performance requirements, and duty cycle (see Table 3):

TABLE 3

	US Units	SI Units
Weight of aircraft (WA)	425 000 lbf	1890.5 kN
Aircraft engine thrust (ET)	5 000 lbf	22.24 kN
Coefficient of rolling resistance (f)	1.5%	1.5%
Coefficient of breakaway resistance (f_B)	4%	4%
Maximum push-out speed (V) on level surface	2.5 mph	4 km/h
Maximum tractor speed (V) on level surface	8 mph	12.87 km/h
Maximum acceleration (a)	0.015 g	0.015 g
Maximum surface grade (G)	2%	2%
Coefficient of traction (u)	0.57	0.57
Efficiency of drivetrain (e_D)	0.85	0.85
Gate duty with average number of push-out operations per hour	2	2
Daily duty cycle	16 h	16 h
Battery charging cycle	8 h	8 h
Average push-out distance (S_T)	300 ft	91.5 m
Average distance of travel after each push-out operation (S_R)	500 ft	152.5 m

4.6 (Continued):

Assume that the coefficients of breakaway and rolling resistances for the tractor and aircraft are the same as shown.

a. Drawbar Pull: Using Equation 20, the required drawbar pull at breakaway is:

$$DBP_B = (f_B + G)\ WA + ET$$

In US Units:

$$\begin{aligned} DBP_B &= (0.04 + 0.02)\ 425\,000 + 5000 \\ &= 0.06 \times 425\,000 + 5000 \\ &= 30\,500\ \text{lbf} \end{aligned}$$

4.6 (Continued):

In SI Units:

$$\begin{aligned} DBP_B &= (0.04 + 0.02)\ 1890.5 + 22.24 \\ &= 0.06 \times 1890.5 + 22.24 \\ &= 135.68\ \text{kN} \end{aligned}$$

b. Weight: Using Equation 22, the required weight of the tractor is:

$$WT = \frac{DBP_B}{u - f_B - G}$$

In US Units:

$$\begin{aligned} WT &= \frac{30\ 500}{0.57 - 0.04 - 0.02} \\ &= \frac{30\ 500}{0.51} \\ &= 59\ 804\ \text{lbf} \end{aligned}$$

Rounded WT = 60 000 lbf

In SI Units:

$$\begin{aligned} WT &= \frac{135.68}{0.57 - 0.04 - 0.02} \\ &= \frac{135.68}{0.51} \\ &= 266.04\ \text{kN} \end{aligned}$$

Rounded WT = 266 kN

c. Power: Since the power of the drive system is proportional to the total resistance and speed (see Equations 23 and 24), the total resistance of motion during different phases of the push-out operation must be determined and then the required power of the drive motor(s) can be calculated. The performance characteristic (curve) of the drive motor(s), which shows the relation between the output power and rotational speed of the motor, must meet the power requirements of the vehicle drivetrain.

Using Equation 13, the total resistance during different phases of the specified push-out operation can be calculated and then by Equations 23 and 24 the required motor(s) power can be determined as follows:

1. During push-out with maximum acceleration, a = 0.015 g, at a speed V = 1 mph = 1.609 km/h:

$$TR_M = \left(\frac{a}{g} + f + G\right)(WA + WT) + ET$$