Transport Science for Operations Management

Understanding elementary physics and mechanical engineering

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Prologue

In developing and using a transport system, both economists and engineers are needed. Their field of operation will overlap in some degree, but their interests will differ. If they want to co-operate effectively they must be able to communicate with each other - and to that end they must understand the possibilities and impossibilities of each other's discipline. The intention of this booklet is to provide economists, and in particular operations managers, with a basic level of understanding of the physical and mechanical aspects of transport, both in the large (e.g. ocean ships) and in the small (e.g. inventory stacking).

In our experience, students of our target population are best helped with **clear definitions** and **numerical examples** related to **operational practice**. So we have concentrated on these points. Admittedly, the link to operational practice has not become as strong in these pages as should be the case, but we are working on that. It already helps that there are some photo's and details of actual operations - see our acknowledgements below. Also, nowaday one could use the internet to show cases and machinery. There are some links in the appendix.

K.F. Drenth Th. Cool

Reading notes

(1) Studying is not a one-way street. Students should work actively on these issues. You as a student will better understand this subject if you try to imagine for yourself where transport science will be useful for you in practical logistics. Examples that you find yourself might be more convincing to you than the examples that we have provided. There are some more study notes in the appendix.

(2) Most of the models presented here have also been implemented in *Mathematica.* See for example the package TScience` in Cool (1999). This means that you could easily look into the effects of parameter changes. There are also other software programs that you can use, see the links provided below.

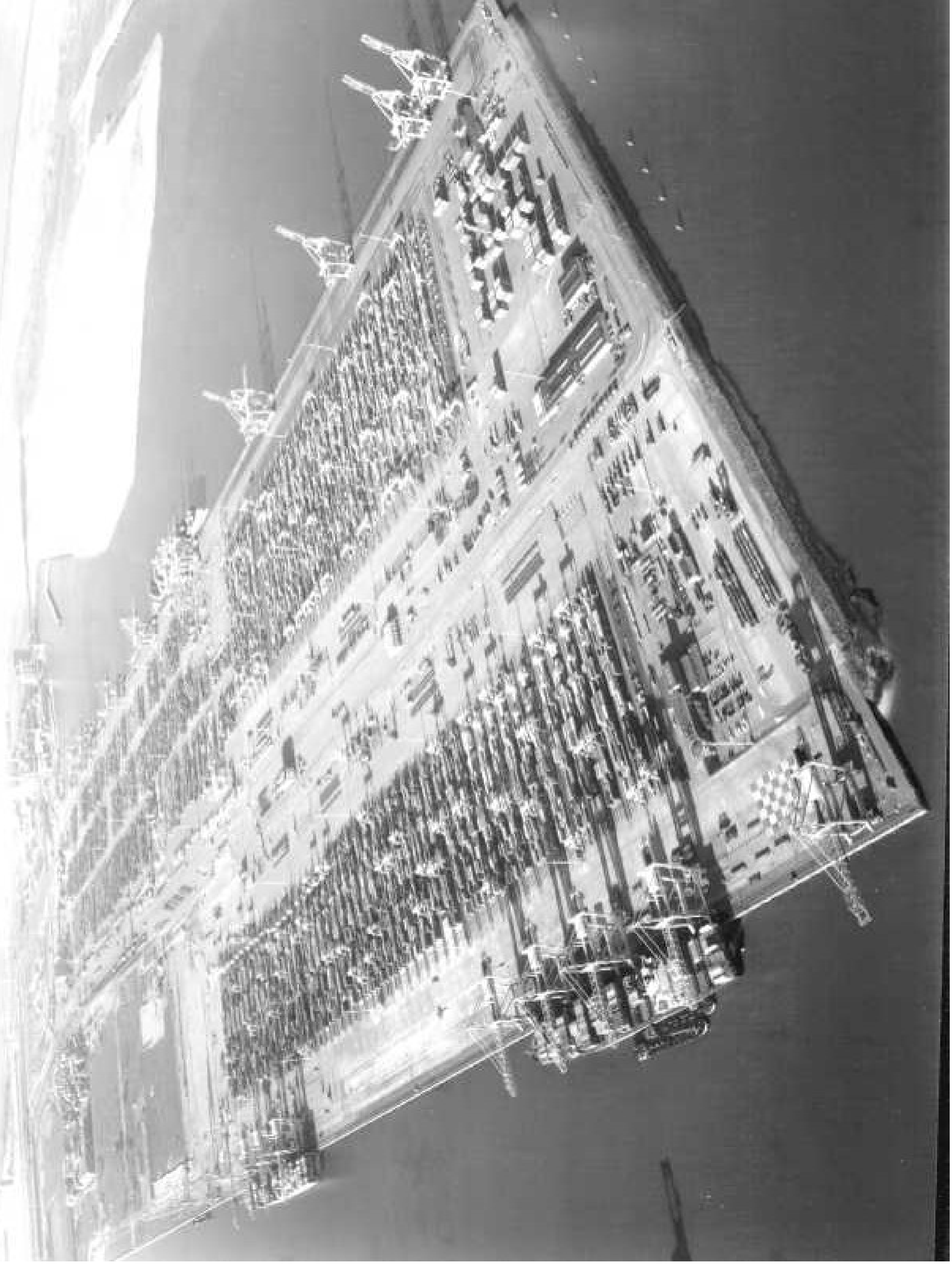
(3) Dimensions will frequently be denoted between straight brackets. For example a speed of a hundred meters per second will be denoted by 100 [m / s]. In this manner there is a clear distinction between variables and dimensions. E.g. there is the mass *m* and the unit distance [m] meter. However, when no confusion is possible, the straight brackets might not be used.

Brief contents

Contents

Greek alphabet

Α, α	Alpha	Ι, ι	Iota	Ρ, ρ	Rho
Β, β	Beta	Κ, κ	Kappa	Σ, σ, ς	Sigma
Γ, γ	Gamma	Λ, λ	La(m)bda	Τ, τ	Tau
Δ, δ	Delta	Μ, μ	Mu	Υ, υ	Upsilon
Ε, ε	Epsilon	Ν, ν	Nu	Ω, ω	O-mega
Φ, ϕ, φ	Phi	Ο, ο	O-micron	Ψ, ψ	Psi
Χ, χ	Chi	Π, π	Pi	Ξ, ξ	Xi
Η, η	Eta	Θ, θ, ϑ	Theta	Ζ, ζ	Zeta



1. Introduction

Economics and technology share their focus on efficiency. Income and welfare can be improved *either* by new techniques and more technology *or* by improvements in the social organisation that uses existing techniques, *or* by a combination of these. When modern firms try to compete as close to the efficiency frontier as possible, they place themselves at the intersection of economics and technology where the issue of efficiency is most acute. In that case a basic appreciation of both subject areas and their interaction becomes crucial. Operations managers will not only benefit from some general knowledge of technique and technology, but in many respects they simply cannot do without.

The following may be an eye-opening analogy. Operations management deals with place, time, quantity and quality. Elementary Newtonian physics deals with place, time and quantity too. So clearly, operations and engineering are on common ground. Issues of **storage** (place), **transport** (speed) and **transshipment** (acceleration) have physical aspects that are relevant for the operations manager. A fourth component is **information**. The basic links between the professional subject matters are again tabulated in Table 1.

Table 1: Basic links

Operations	Engineering
storage	place
transport	speed
transshipment	acceleration
information	computing

The physical and mechanical properties of the means of storage, means of transportation, and means of transshipment are clearly relevant for who have to decide about their deployment to the best results for the firm.

We will encounter these direct links over and over again.

Goods take different shapes, and the equipment and tools to handle these goods will be selected to suit these shapes. Sometimes it appears useful to change the shape of the goods, so that they can be handled easier. A typical example is that manload sizes are adapted towards either bulk or larger unit sizes, to facilitate machine handling. Table 2 reviews the matter.

We are dealing not only with transport but also with transshipment. In general we shall be dealing with vehicles and infrastructure, where terminals and means of storage are part of the infrastructure.

A key notion is that 'transshipment' practically always requires a storage phase. This is true in the large (a container terminal) and in the small (when a bulk grab unloads into a bunker that feeds the conveyer belt). Storage is the way to change a continuous flow into a discontinuous flow and vice versa. When the speed at which goods are arriving differs from the speed at which they are departing, there is a buffer involved, and thus an area to store the goods and the tools to handle them. And these come with costs.

We shall be concerned with huge quantities. A 250,000 dwt ship loaded with coal arriving in Rotterdam harbour needs to be unloaded into 72 river barges of 3500 dwt, and these again will have to be unloaded at the electric power plants up the Rhine.

Table 2: Classification of goods and tools

Meters	Appearance	Class	Tools
10^{-5}	gas		
10^{-4}	fluid		pneumatical
10^{-3}	powder	Bulk	hydraulic (e.g. slurry)
10^{-2}	granular		mechanical (grab, screw, conveyer)
10^{-1}	bricks		
10^{0}	units ([1])		manload = 1 - 55 kg and 0.1 - 0.55 m
10^{1}	units	Units	mechanical (crane, forklift, straddlecarrier)
10^{2}			

[1] Goods of manload size are changed into bulk or unit format, for machine handling.

Another example is the Rotterdam power plant in combination with the EMO ("Europese Massagoed Overslag") terminal in Rotterdam harbour. The Rotterdam power plant requires some 2 million tonnes of coal per annum, and produces at least some 400,000 tonnes of waste. The coal ships are unloaded by crane and grab (discontinuously) and the coal is transported by conveyer belt (continuously) to the power plant. The plant of course has a storage facility. To facilitate burning, the coal chunks must be grounded to granular shape (though this is increasingly done at the mine, also in order to increase the density during transportation). Key data are in Table 3. Note that EMO also provides for many other customers in Europe.

Table 3: Key data on the Rotterdam power plant and EMO terminal

Aspect	*Quantity*	*Tool*	*Property*
annual coal use	2 million tonnes	crane height, width	70 m, 140 m
annual output	6 million MWh	crane weight	2600 tonnes
waste gypsum	120,000 tonnes	gross grab weight	85 tonnes ([2])
waste slag	40,000 tonnes	top performance	5100 t / h ([3])
waste ashes	240,000 tonnes	cable diameter	56 mm
per furnace	180 t / h ([4])	electro motors	110 à 0.75 - 720 kW
per ship	250,000 tonnes	lift speed	3 m / s = 10.8 km / h
per train car	20 - 30 tonnes	horizontal acceleration	0.8 m / s^2

Economic and operational questions that clearly require knowledge of science are:

- Is it is better to transport coal by ship or electricity by cable ?
- Would it be an idea to expand EMO ?
- Also, suppose that EMO is to double, will it be feasible to double the size of the equipment? Could we double the size or the speed of the grab, and what does this mean for the crane ?

[2] The grab itself weighs 35 tonnes, its load 50 tonnes. 1 tonne can be seen as a medium sized passenger car. The grab hold is about 3 by 3 by 5 meters, with a content of 45 - 50 m^3. Coal weighs about 1 tonne per m^3. When the grab is opened, 50 tonnes of load crashes into the bunker, and dust particles have been traced to distant places in the country.

[3] A cycle takes 45 seconds, so there are 80 cycles per hour, so 50 tonne / cycle * 80 cycles = 4000 t/h.

[4] This is the equivalent of 145,000 m^3/h of natural gas, while a household uses about 5,000 m^3 per annum.

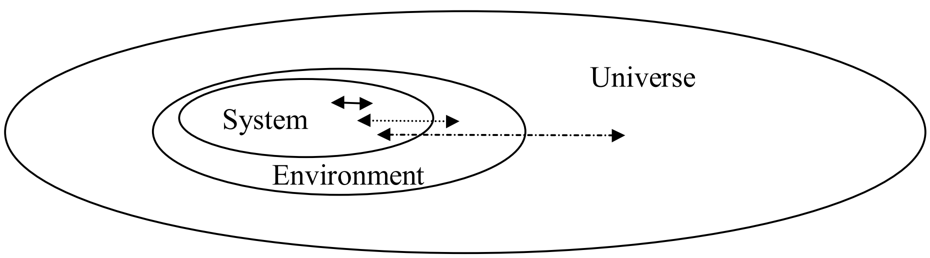
- When the grab moves much faster, what are the consequences of an unfortunate crash of its 85 tonnes onto the ship's hull ?
- Since cranes are on the quay, at vertical slopes with the water, they require special building techniques (especially in sand grounds in Holland).
- If output is to double, so will the waste, and how can we deal with the traffic ?

It are questions like these that motivate our interest in 'transport science'.

Systems approach

While reading these chapters, the reader may benefit from having the systems approach in the back of his or her mind. This approach recognises *elements* and their *relations*, and locates a system within its environment within a wider universe. Figure 1 contains an overview of these concepts. The arrows denote relationships, and the relationships will be clearest for the system itself and weaker and vaguer getting outside the boundaries of the system.

Figure 1: Systems approach



Note that an element within the system itself could be a 'black box' for the system. A black box element is not explained by the system, and hence that *explanation* (i.e. the explanation and not the element itself) would fall in the outer universe that is not considered by the system.

The systems approach is useful to cause a shifts of focus. What is efficient in one point of view, may appear to be inefficient in another point of view.

For example, in a sugar factory, beet pulp is processed, and a sugar solution is condensed to syrup and sugar cristals. The factory uses huge amounts of energy to make cristaline sugar. This sugar then is transported in bulk to other factories. One such factory will be a confectionery plant. The first step in that confectionery plant

will be to ... dump the sugar into water tanks ! We have two conclusions. (1) Clearly, each part of the process can be regarded as a small system, and here each subsystem has been optimised to efficiency, i.e. sugar making by itself, transport by itself, confectionery making by itself. (2) But by shifting the focus to the whole process, one starts wondering whether the transport should not concern cristaline sugar but a sugar solution, and, since transporting water is not too efficient, whether the two plants should be located close to each other so that a pipe might do the work.

Structure of the discussion below

We start with the basic properties of vehicles and terminals. The drive towards cost reduction leads to larger vehicle sizes, and these again put strains on the equipment. We clarify the issues involved in expanding the number of docks versus the speed of handling at existing docks. This issue is tackled by looking at ships and ports in particular. This discussion should provoke the appetite for more insight in what engineers think of these issues.

There is a short refresher chapter on elementary mathematics. Students will obviously have difficulty with the remainder when they lack some basic mathematics. We use three pages to restate the main definitions and to clarify these, as definitions are the key to understanding.

The chapter on ‘distance and time’ restates the ‘place, speed, acceleration’ mantra of the common ground of operations managers and engineers. The discussion of road capacity is a practical application that helps operation managers to understand why our roads are congested and why this cannot be simply changed.

Then we introduce Newtonian Mechanics, and apply this to storage of bulk commodities. The angle of repose is explained, and maximal versus average pressure on the storage foundations.

The subsequent discussion on mass and volume flows brings us to one of the key issues in transshipment operations: the choice between continuous and discontinuous methods.

In a semester setting, the subsequent chapter on energy would complete the first semester. The notion of energy is crucial in understanding natural phenomena. And it is crucial for economics and operations, since energy is a large cost item. Understanding energy helps finding ways towards more efficiency (and helps defining efficiency).

We continue with vehicles. It is useful to remember that vehicles are ‘discontinuous instruments’ as this affects operations. The chapter on resistance explains the mechanical user costs of vehicles. Note that this chapter relies on the former chapters, since we require both forces and densities (namely air density).

The issues discussed in this chapter give a clear insight in the issues of (national) transport policy.

The discussion on momentum help us to understand the dynamics of vehicles. We discuss toppling cranes, and return to the issue that trucks cannot brake as fast as passenger cars, which again links with the capacity of the transport network (at your factory or port).

The discussion of angular motion should not come as a surprise, since much of our transport relies on wheels. For lifting objects, we use pulleys. To control motion, we use transmissions. This chapter helps to understand the forces involved, and hence the wear and tear, and durability of the equipment.

The chapter on transformations is an obvious engineering elaboration on the issue of efficiency. Transforming one kind of motion into another kind costs heat, and it is useful to understand why and how.

Finally, we arrive at materials science. How does steel behave under the stresses that we subject it too ? We don't only better grasp speed limits and the limits to growth, but also better understand how corrosion, fatigue, creep and combinations of these cause maintenance costs and such.

Example questions

1) European law allows that trucks have a width of 2.5 meters. This width is important for road properties. It also relates to handling, since, for example, two pallets are placed next to each other, allowing for loading and unloading manoeuvering space, and for some sagging of the stacked goods.
   It is on the news that the European ministers of Transport are meeting to discuss a dispensation for 'conditioned goods', i.e. cold storage transport. The proposal is to allow a width of 2.6 meters for this category. However, one would suppose that European ministers have much more important issues to discuss than a mere 10 cm for a small category of road transport.
   Give your best guess why these ministers discuss this issue. And, should they allow this dispensation ?
2) A factory building contains a turbine generator and a condensor. Once a year, a part of this equipment has to be checked, and a 10 tonnes heavy part has to be lifted aside, for say five meters. To do this, the building engineer proposes to construct a trolley at the top of the building. This will require a steel construction that can carry the trolley, the 10 tonnes, and its own weight. The whole construction appears to be expensive. What is your suggestion ?

(Answers are in the back.)


CHO YANG ACE

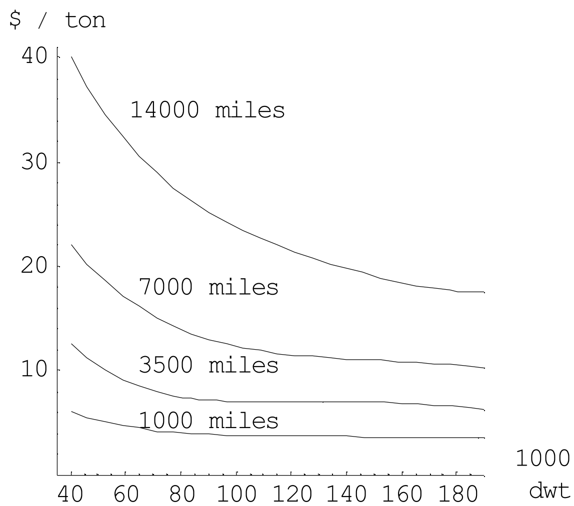
2. Example environment of application: Ports

Though trains and trucks could be used too, we have selected ports as an example of the environment for which transport science is an essential subject.

Ship sizes

When transporting over long distances, the economic pressure is for big ships. Figure 2 gives the shipping costs per ton as a function of ship size and (one-way) sailing distance in nautical miles. Clearly, the larger the distance, the cheaper it is to use a larger deadweight (dwt) size.

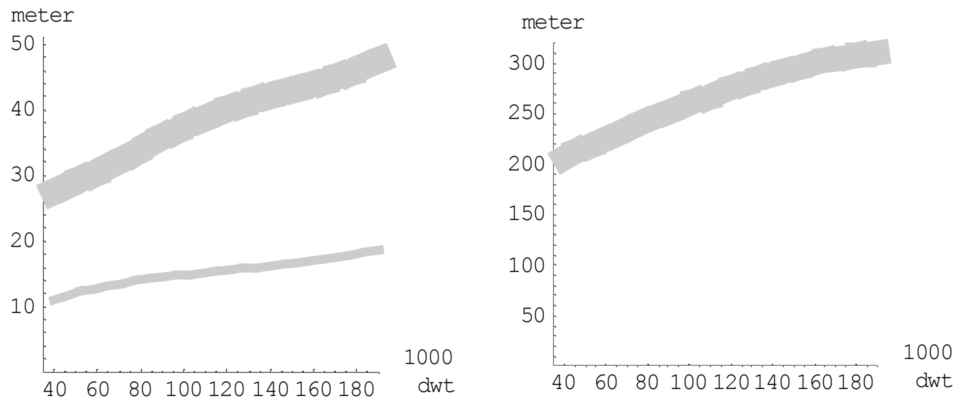
Figure 2: Shipping costs per ton as a function of ship size and one-way sailing distance in nautical miles



The size of a ship translates into draft, width and length. Figure 3 plots these parameters.

The ship parameters on draft, width and length have a direct impact on harbour parameters of depth, quay length and strength, handling tools. Investments in infrastructure have a direct relationship to waiting and service times. All these costs must be balanced. The next section looks into this more deeply.

Figure 3: Draft (left bottom) and width (left top) and length (right) of ships, in relation to dwt size



Port equipment

To deal with the increased size of ships, ports have developed numerous pieces of equipment. The following is a short list of major items. We also include some technical terms that are used in the application of the equipment.

AGV = automatic guided vehicle (EUR 140,000 a piece) that drives in saveguarded area

ASC = automatic stacking crane (also stores information where containers have been stacked). These can be ‘rail mounted’ or ‘rubber tired’.

berth = part of a quay where a ship can be loaded and unloaded, 22 meter to the sea bottom to allow for a draft of 20 meter, 300 meter long (at EUR 25,000 per meter = EUR 7.5 million; with additionally 4 cranes this is EUR 40 million per berth)

broom clean = state of the ship load area when fully cleaned

BSC = barge service center

crane = a crane of 90 m high may weigh 1000 tonnes, and cost EUR 7 - 9 million

distripark = location where ‘value added logistics’ can take place. Includes maintenance of containers, like damage repair

double stack trailer (DST) = trailer with 2 x 2 = 4 containers. With 30 tonnes per container, the load is 120 tonnes. This is used in Singapore, and the disadvantage is continuous damage on the vehicle.

empty = an empty container

kick in - kick off = movements of a grab. The kick in is when the grab moves into the ship, the kick off is when it moves sideways in the ship's hull.

MT = multitrailers = 1 driver and for instance 5 trailers, at a cost of EUR 340,000 (EUR 140,000 per tractor, EUR 40,000 per trailer). With two containers on a trailer and with two axes per trailer, the weight per axis is 25 - 30 tonnes. The speed of the MT is 25 km/h. The key notion of the MT is that the trailers follow exactly the tractor's trace.

pay loader = carterpillars loaded into the ship to sweep up remaining cargo, so that the grab can reach it and clean out the ship

reach stacking = stacking to reach a particular container. E.g. to find a container at the bottom, the containers on top need to be moved.

RSC = rail service center

spreader = frame with four flippers on which the container is fastened for lifting. The spreader itself may weigh 12 tonnes

stacking area = area where containers are stacked. Normally, there is a balance between the size of the area and the stacking or cycling time (see reach stacking)

straddle carrier = A straddle carrier is a vehicle to move containers. It can 'sit' over the container, along its length, and then lift it and drive it to some other place, e.g. put it on a truck. When stacking "4 over 3" the driver sits at least 4 * 8' = 32' above ground.

Berth utilisation

This example discusses the case where it is more economical to increase the handling speed of an existing berth rather than building another berth next to it.

Regard 80 ships of 100,000 dwt annually arriving at a berth in a harbour, giving a throughput of 8 million tonnes. The following factors affect the process time:

1) waiting time, determined by
   a) arrival rates
   b) number of berths
   c) availability of free berths
   d) handling and departure rates

2) unloading time, determined by
   a) quantity of the load
   b) kind of ship
   c) kind of load
   d) handling capacity itself.

Let us consider some basic queueing aspects. [5] A year has 8760 hours around the clock for 365 days. So the system hours are 109.5 [hour/ship]. The mean arrival rate thus is $\lambda^* = 1/109.5$ [ship/hour]. At $\rho^* = 60$ % utilisation, and a single berth, the mean service rate is $\mu^* = \lambda^* / \rho^* = 0.0152207$ [ship/hour]. In a queueing model assuming independent interarrival and service times, we then can determine the hours that a ship is being served at the berth and the hours that it is waiting outside the harbour. The sum of these are the total process hours that the ship takes waiting and unloading. These results per ship we can again multiply by 80 ships to find these hours for the whole fleet. These data are summarised in Table 4 (including the alternatives that we regard next). You may check that the service hours for the ships are 5256, and these overlap with the utilisation hours for the harbour, giving 5256 / 8760 = 60 %.

Table 4: Queueing data at 60% and 30% harbour capacity utilisation

per ship	*Utilisation*	*Service hours*	*Queue hours*	*Process hours*	*System hours*
1 berth	60%	65.7	98.55	164.25	109.5
	30%	32.85	14.	46.9	109.5
2 berths	30%	65.7	6.5	72.2	109.5 (*2)
80 ships	*Utilisation*	*Service hours*	*Queue hours*	*Process hours*	*System hours*
1 berth	60%	5256	7884	13140	8760
	30%	2628	1126	3754	8760
2 berths	30%	5256	520	5776	8760 (*2)

In this case, it appears that the shipowners are of the opinion that the process takes too long. Though servicing takes less than 3 days, the whole process takes 7 days per ship. The shipowners are willing to pay a premium if the harbour can speed up the process. There are two possible configurations:

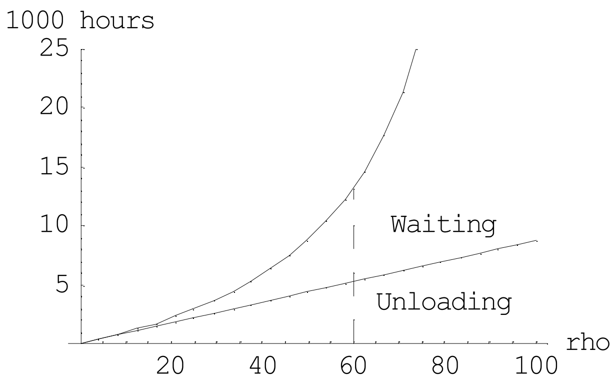
[5] Queuing theory uses λ for the arrival rate, μ for the service rate and ρ for the degree of utilisation. In physics, μ is a friction parameter and ρ is the density. To prevent confusion, we write the queueing variables with a star affixed.

- The first option is to maintain only one berth but to speed up its handling capacity, e.g. by adding another crane. In that case utilisation drops to $\rho^* = 30$ %. The queueing properties remain the same, and the calculations straightforward.
- The alternative is to build another berth, while using the same handling technique and speed. Utilisation of the harbour again drops to a nominal $\rho^* =$ 30 %, but the queueing properties change, so we cannot simply perform the same calculations. The results of the more complicated model however are tabulated in Table 4 too.

In answer to the shipowners, the harbour authorities would favour the upgrading of the single berth, at least in normal conditions.

Figure 4 dramatises the situation by plotting the annual total hours as a function of ρ^*. The figure shows that total annual service time (for unloading) is proportional to capacity utilitsation (namely per definition 8760 ρ *) and that waiting time depends upon the queueing model (in this case for the single berth). Small increments in the arrival rate can cause long queues.

Figure 4: Occupancy in hours per annum



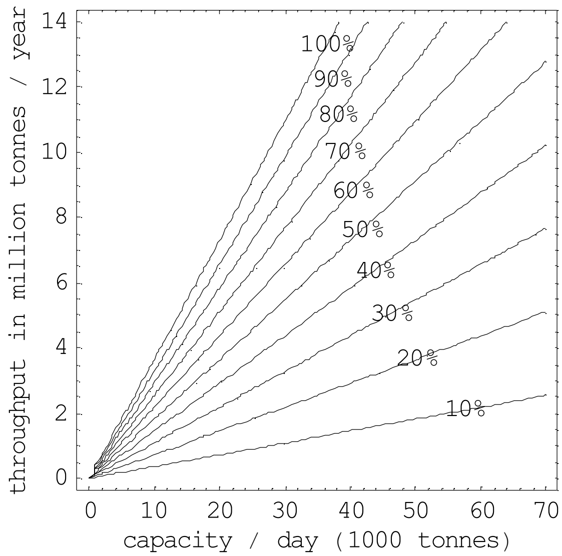
We can also calculate that 60% capacity utilisation at a throughput of 8 million tonnes implies a capacity of 13.3 million tonnes, and with 365 days per year this is 36,529.7 tonnes per day. These data can also be found in Figure 5 that plots the capacity-versus-throughput-space, with the different utilisation rays. Another example in the figure is that a throughput of 8 million tonnes per year at 30% utilisation requires a capacity of 73 thousand tonnes per day.

However, handling huge quantities at high speeds, meets with physics. The current size of the EMO grab of about 3 * 3 * 5 = 45 m^3 is close to normal physical limits,

and therefor new developments are in the direction of continuous rather than discontinuous unloading.

It is from considerations like these that owners of ships and harbours have developed a keen interest in material handling, both the methods and the equipment. And these points clarify why some understanding of physics is so important.

Figure 5: Terminal utilisation rays



Lifting tools

We will discuss the choice of discontinuous or continuous lifting methods further below.

Presently, it is useful to become aware of the fact that the use of the grab to lift material still is rather superior compared to other methods. Table 5 contains a review of methods and tools for the vertical lift, [6] and Table 6 contains some key data (some of the symbols will be explained later). It appears that other methods than the grab still have many problems. This also causes that there is little experience with them.

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[6] Note that these methods may also be used for horizontal lifts. However, horizontal lifts can also be done by truck, ship and other modes of transport. So the key to the table is that these methods are capable of vertical lift, as distinguished from 'horizontal lifts only'.

Thus, when a tool manufacturer approaches a terminal operations manager with a new tool design, he or she is well advised to respond “Go to my competitors, and let them try it first”. Also, terminals that do take the risk of trying new tools, then arrange huge discounts with the manufacturers, to compensate for the associated costs.

Table 5: Methods for vertical lift

Methods					*Remarks*
discontinuous	grab				
continuous	**with medium**	air	pneumatic		Not uncommon for granules
		fluid, slurry	hydraulic		Example in Alaska
	without medium	mechanic	form closure	disc elevator	Within a pipe, a central cable lifts small discs (platforms) that carry the material [7]
				flexowell [8])	The belt has evenly spaced bars that create ‘cells’ that contain the material
				bucket elevator	Buckets are affixed to the belt
			force closure	sandwich belt	The material is squeezed between two belts, and remains there because of friction [9]
				pipe belt	The belt first is flat, and then distorts to a pipe, holding the material
				screw	Most common (Siwertell [10])

[7] Used in Amsterdam / Zaanstad to lift cocoa. Quantities are limited.

[8] A conveyer belt has to be flexible in order to make it around the far ends. If a belt is not entirely flat, and has some vertical sides to keep the material in, then these sides have to make the turn too. The latter design makes such belts expensive. A ‘flexowell’ belt costs $ 0.8 million and has a limited life span.

[9] This uses a wheel that scoops the material and throws it between the two belts.

[10] Friction is huge here. The Siwertell machine that is used in Amsterdam harbour has a screw of 2-2.5 cm thick steel, and though only ‘soft’ products are unloaded (i.e. agricultural products like grain) it still has a life span of only 3 months. Note: it takes two days to replace it.

Table 6: Some key data

	Bucket elevator		Concave [11] belt conveyer		Pipe belt conveyer	
speed v (m/s)	1.6	4.0	3.35	5.24	5.24	7.4
width B (m)	.125 - 1	.125 - 1	.5 - 1.6	.5 - 1.6	.15 - 1.6	.15 - 1.6
elevation h (m)	20 - 30	20 - 60	20 - 60	20 - 60	20 - 60	20 - 60
tonne / hour	12.5 - 275	50 - 315	200 - 3000	320 - 4700	15 - 1900	20 - 2600
max angle (°)	75	75	22.5	22.5	90	90
granular or sticky material	granular only	granular only	both	both	both	both

Example questions

1. Quay days and handling effort

The idea behind the following question is: In the choice of the number of berths, one must balance waiting time with investment costs of quay length. The numbers of containers and their unit weight will cause tough requirements on the handling equipement.

Given is: Regard container ships of 4000 **TEU** ([12]) with a load factor of 80%.

Berth throughput is 400,000 TEU / year.

The average handling time is 2 days.

1) Determine the number of ships per year and the number of quay days.
2) The load consists of 20’ and 40’ containers, with the **TEU factor** (= # TEU per container) = 1.6. Determine the numbers of 20’ and 40’ containers.

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[11] The belt is a bit curved, so that the transported material does not fall off the sides.
[12] Twenty ft. Equivalent Unit. The 1 TEU standard container is 8’ wide, 8’ high, and 20’ long. It has a content of 1280 ft^3 or 36.25 m^3, and may weigh as much as 30 tonnes.

2. Unloading time

The idea behind the following question is: Reduction of the number of berths (quay length) or the number of cranes per berth, reduces investments, and improves the return on capital. However, it also increases waiting times. Thus too low an investment causes costs on exploitation (while it may be difficult to change the infrastructure). On the other hand, when there is overcapacity, then too few activities have to bear the capital burden. (Thus: (a) warrant good demand projections, (b) arrange sharp arrival and departure times.)

Given is: In theory, unloading at the harbour requires 1 container / minute = 60 * 24 c / day = 1440 c / day.

However, opening the hatches, releasing the clamps, moving the cranes, changing crane drivers, etcetera, cause an average of 700 - 800 c / day (or about 2 minutes / c).

Using a maximum of 5 cranes / ship, gives 3500 - 4000 c / day.

1) With 4000 TEU ships at 80% capacity and a TEU factor of 1.6, what is the average unloading time, using 5 cranes at a speed of 800 c / day / crane? (Note: this is still fast.)
2) Let the lift height be 40 meters with respect to the quay. With a ship draft of 20 meters, the average vertical distance is 50 meters. Let the ship width be 44 meters and the used quay width be 15 meters. Lifting squarily (not roundly) [13] and with 1 minute per container, what is the speed of the **spreader** that moves the containers in and out of the ship ?

3. Demands on stacking area

The idea behind the following question is: When land is expensive, stack higher. The additional advantage is shorter driving distances. However, stacking also requires (a) stronger foundations, (b) better stacking equipment and drivers willing and able to work e.g. at 12 meters high, (c) stacking & cycling time.

Given is: Throughput at the harbour is 400,000 TEU / year, with a TEU factor of 1.

Number of working days is 300 days / year

Average storage in stack lasts 3 days.

The **peak factor** is 1.5, i.e. that the stack in peak times contains 1.5 the average amount.

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[13] 'Lifting squarily' means that the up and side movement are at right angles. 'Lifting roundly' means that one cuts corners. The latter is quicker, but also has the danger of hitting the hatches or hull.

Use a **straddle carrier**, that requires 1 meter driving space on both sides of a container, along the length of the container.

Determine the size of the area needed, in m^2, with 1' = 0.3048 m, for the two possibilities:

1) A straddle carrier with 2 over 1.
   This supposes that the containers are simply put on the ground, and not stacked on top of each other. The straddle carrier must still be able to lift one container across the other, so the lift height still must be 16' = 4.88 meters (exclusive of cabin and equipment).
2) A straddle carrier with 4 over 3, but with an average stacking height of 2.3 containers.
3) What happens when the TEU factor changes ?

4. Berth utilisation

A terminal has only one berth, for ships of 80,000 tonnes carrying granular material. Throughput is 5 million tonnes per year, and the capacity is 2000 tonnes per hour. The working year is 360 days, with 10 idle days per year. The waiting time in the queue can be given as WT = 1000 ($e^{3\rho^*}$ - 1) hours/year for all ships, where e is the base of the natural logarithm and ρ^* is the degree of utilisation of the berth. Give the expected time in the harbour per ship.

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3. Elementary Mathematics

Pythagoras's Theorem

We shall be using Pythagoras's Theorem frequently. Figure 6 contains a triangle with sides *a* and *b* in a straight angle, and hypotenusa *c.*

Pythagoras's Theorem is that $c^2 = a^2 + b^2$.

Figure 6: Triangle with straight angle

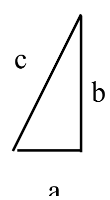
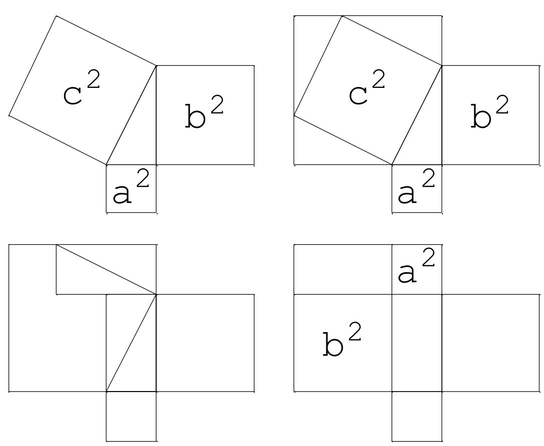


Figure 7 contains a graphical proof of the theorem. The squared powers a^2 , b^2 and c^2 are associated with the surfaces of squares. By drawing the big square with sides *(a + b)* and eliminating the surfaces of the four 'side triangles', we find the equality proven

Figure 7: Proof of Pythagoras's Theorem



The proof can be worked out algebraically too, by noting that the surface of the big square is given here as $c^2 + 4$ (½ a b) while it also must be equal to $(a + b)^2 = a^2 + 2\, a\, b + b^2$. This then solves into the equality stated by the theorem.

Definition of distance

A point $p = \{x, y\}$ in twodimensional (Euclidean) space can be regarded as a vector. The length of the vector can be denoted as $\| p \|$ and can be defined by means of Pythagoras's relation:

$$\text{length}(p) = \| p \| = \sqrt{x^2 + y^2}$$

The distance between two points $p = \{x_1, y_1\}$ and $q = \{x_2, y_2\}$ in twodimensional (Euclidean) space can be found by regarding one point as the origin and by then taking the length of the remaining vector (the difference):

$$\text{distance}(p, q) = \| p - q \| = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

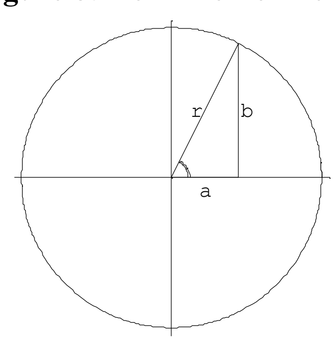
Definition of a circle

A circle with center $\{x, y\}$ and radius r is defined as all points $\{a, b\}$ at distance r from that origin. In other words:

$$\text{distance}(\{a, b\}, \{x, y\}) = r$$

The circle with center $\{0, 0\}$ is drawn in Figure 8. We find that $r^2 = a^2 + b^2$. It thus appears that there is a subtle relationship between the theorem of Pythagoras and the notions of distance and the circle.

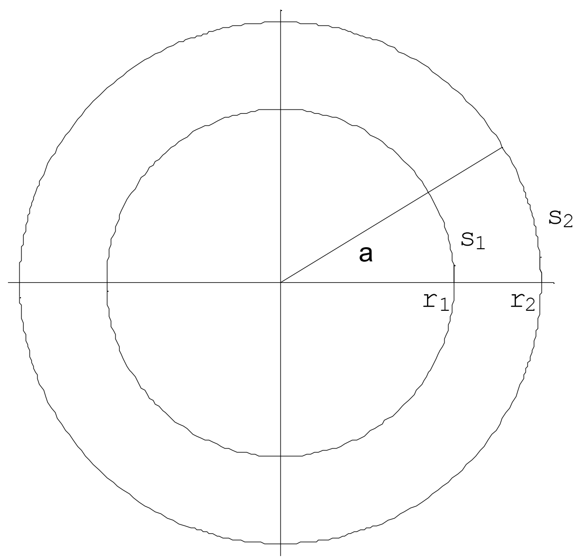
Figure 8: Definition of a circle



Angles and radians

Figure 9 shows how angles and radians are defined. The radius of the first circle is r_1, and the radius of the second circle is r_2. Taking an angle α, then the ratio of the section of the circle with the radius is given as $s_1 / r_1 = s_2 / r_2$,. Since this ratio is constant for α for whatever radius, we define α as that ratio. If we take $r_1 = 1$, then s_1 are the radians. The measurement basis for angles thus is the unit circle with $r = 1$. The circumference of a circle is $2\, \pi\, r$ and thus for the unit circle it is $2\, \pi$. The angle of a full circle is said to be $2\, \pi$ radians.

Figure 9: Definition of an angle



Angles and slopes

By 'angle' and 'slope' we mean different things (or different measurements of the same thing).

Regard the angle that has been arced in Figure 8. Call it α. By dividing a and b by r we get the unit circle. The size of α in radians is given by the arc on the unit circle from the point {1, 0} to the point $\{a/r, b/r\}$.

We use $\sin(\alpha) = b/r$ and $\cos(\alpha) = a/r$ as abreviations for these ratios. (Sinus is 'angle, corner' in Latin.)

Clearly, from Pythagoras's Theorem: $\sin(\alpha)^2 + \cos(\alpha)^2 = 1$, since $(b/r)^2 + (a/r)^2 = 1$.

Slopes are measured in two ways:

1) In everyday traffic, the slope of a road on a hill is measured as the sin() and then expressed as a percentage. For example, a road section of 100 meters (r) is taken, the vertical ascendency (b) between the beginning and end of that section is measured by a long stick and an optical instrument, and the slope then is determined as $b/r = b$ %.
2) Algebraically, the formula for a line is $f(x) = m\,x + n$, with m the slope and n the constant. Here the slope is measured as the tangens, i.e. $m = \tan(\alpha) = \sin(\alpha) / \cos(\alpha) = b / a$.

Note: given the pair $\{r, \alpha\}$ (the polar co-ordinates), one can find $x = r \cos(\alpha)$ and $y = r \sin(\alpha)$. Thus, if the radius and angle are given, then you can derive the co-ordinates, and conversily, if the co-ordinates are given, then you can derive the radius and angle.

Volumes

Table 7 contains a review of the volumes of some basic objects.

Table 7: Volumes of basic objects

Object	*Volume*	*Surface*	*Remarks*
circle with radius r	0	πr^2	circumference $2\pi r$
globe with radius r	$4/3\ \pi r^3$	$4\ \pi r^2$	
cylinder with radius r and height h	$\pi r^2\ h$	$2\ \pi r\ h$	side surface only
cone with radius r and height h	$1/3\ \pi r^2\ h$	$2/3\ \pi r\ h$	side surface only

Example questions

Q1. An angle of 0.42 radians has how many degrees (out of 360°) ?

Q2. Determine the slope of the tangent of a circle at a point found by 0.66 radians.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4. Distance and Time

Distance, speed and acceleration

If an object starts from position $x(0)$ with a speed $v(0)$ and gets a constant acceleration $a(t) = a$, then:

$$v(t) = v(0) + a\,t$$

$$x(t) = x(0) + v(0)\,t + \tfrac{1}{2}\,a\,t^2$$

These relationships can be verified by applying the formulas $v = dx/dt$ and $a = dv/dt$.

There is the classic examply of gravity with $g = 9.8$ [m / s^2]. Let an object be in rest and then fall from the Pisa tower. With zero air friction it falls 490 meters in 10 seconds (assuming this height). Its speed at that moment is 98 [m / s], or 352.8 [km / h]. Figure 10 contains a plot of the three aspects involved.

Figure 10: Acceleration, speed and place

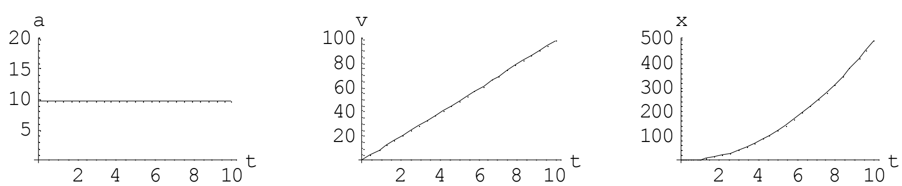


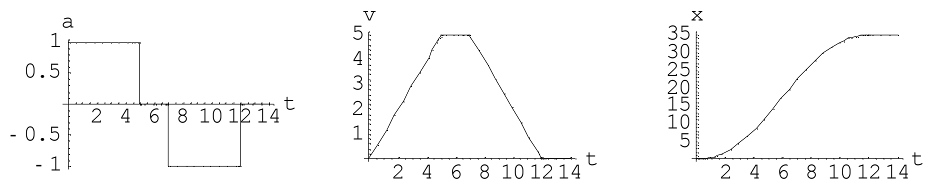
Table 8 summarises the main concepts, symbols and dimensions involved.

Table 8: Distance, speed and acceleration

Concept	Symbol	Dimension	Description
Place	s	m	co-ordinates $\{x, y\}$, Latin: "situs", English: "site". The unit of measurement is the meter.
Length	x	m	distance between two points; for co-ordinates $s(t)$ the distance is $\lVert s(t) - s(t-1)\rVert$ (Pythagoras)
Speed	$v = dx / dt$	m / s	$\lVert s(t) - s(t-1)\rVert / t$ is average speed, dx is the displacement, dx / dt is the instantaneous speed. The unit of measurement of time is the second.
Acceleration	$a = dv / dt$	m / s^2	$(v(t) - v(t-1)) / t$ is average acceleration, dv / dt is the instantaneous acceleration

Figure 11 contains the plot of the acceleration, speed and location of an elevator. For five seconds it has an acceleration of 1 m/s^2. Then the acceleration drops to zero, and the elevator moves at constant speed of 18 km/h for 2 seconds. Then the elevator starts braking at -1 m/s^2. In a total of 12 seconds it moves 35 meters up.

Figure 11: Elevator movement



Road capacity

Regard a single lane road. The capacity of the lane is defined as the number of vehicles per second that can pass through the lane.

This capacity can be determined from some key parameters. Let the vehicles have length L (meter per vehicle), let they drive at a cruising speed v (meter per second), and let these vehicles keep a safe driving distance S (meter per vehicle). The capacity then is $v / (S + L)$ (vehicles per second).

The flow in the lane will be larger when the objects move at higher speed. A clear limit is the speed of light, but there are some more mundane limits. For example there is the optimal speed with respect to fuel use. Another point is that the destination must be able to absorb all arriving objects, for otherwise a queue starts forming that will reduce the speed.

A crucial property of vehicles that constrains capacity is that they might collide. When vehicles collide, the lane blocks and capacity is nil, at least temporarily. So apart from human safety reasons and the costs involved with a collision, there are capacity reasons to prevent collisions.

Note that vehicles may be lined up in a train format to reduce the likelihood of collision internal to that train. But then the possibility remains of collisions among trains.

Let us regard the situation that vehicles move in the same direction but with a sufficiently narrow lane so that when a frontrunner stops the backtrailer may collide into it.

The whole issue now is to find a proper value for S that will prevent collisions.

We can start our analysis with the formulas for $x(t)$ and $v(t)$ above.

Let the frontrunner brake with an acceleration of $-f$, and let the backtrailer have a reaction time of TR and then brake with an acceleration of $-b$. The problem now is to select S such that both are finally at rest, bumper to bumper.

It is most convenient to take the situation of rest as the starting point, and reason backwards (run the movie backwards). In the situation at rest $x(0) = 0$ and $v(0) = 0$, so that:

$$v(t) = a\,t \qquad \& \qquad x(t) = ½\, a\, t^2$$

$$\text{so that} \quad x(t) = ½\; v(t)^2 / a$$

For the two vehicles in backward motion, the acceleration now is positive, and we find the braking distances $x_f = ½\; v^2 / f$ and $x_b = ½\; v^2 / b$ where v is the cruising speed referred to above.

The backtrailer also has a reaction time TR in which a distance $v\ TR$ is covered.

The distance covered by the backtrailer, corrected for the driving distance S, must be equal to the braking distance of the frontrunner. Hence:

$$x_f = x_b + v\ TR - S$$

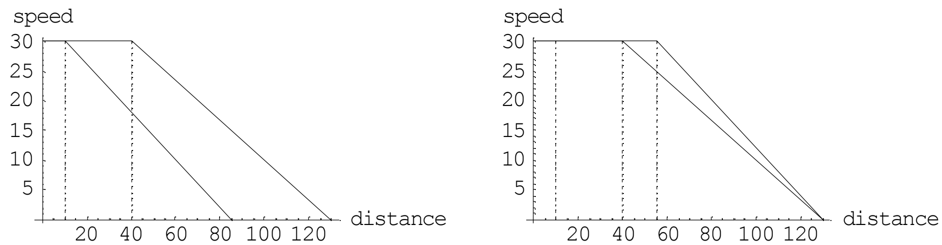
$$S = v\ TR + ½\; v^2 / b - ½\; v^2 / f$$

$$= v\ TR + ½\; v^2\,(1/b - 1/f)$$

For example, if the cruising speed is 30 m/s = 108 km/h, and when $f = 6$, $TR = 1$ and $b = 5$ (which is the unfortunate condition that the backtrailer does not brake as fast as the frontrunner), then $x_f = 75$ m, $x_b = 90$ m, and $S = 45$ m.

This situation is depicted in Figure 12. In the left graph hypothetically both vehicles drive next to each other, vehicle 1 starts braking at $x = 10$ m, and vehicle 2 at $x = 10$ + reaction distance = 40 m. The safe driving distance then shows up as the distance between the vehicles when they both are at full rest, and here vehicle 1 comes to a stop at $x = 85$ m and vehicle 2 at $x = 130$ m. In the right graph the proper situation is depicted that vehicle 1 starts braking at $x = 55$ m, while vehicle 2 is at the safe driving position of 55 - 45 = 10 m.

Figure 12: Safe driving distance



Substituting the relation found for *S* into the formula for the capacity, gives:

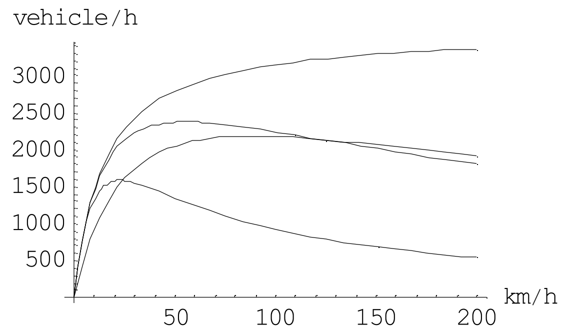
$$Capacity = \frac{v}{S+L} = \frac{v}{v\,TR \;+\; \tfrac{1}{2}\, v^2\,(1/b \;-\; 1/f) \;+ L}$$

Obviously, capacity can be large when reaction times are low and when two vehicles can brake at the same acceleration ($b = f$). These conditions however are rather ideal. A conventionaly measure of capacity assumes that the frontrunner makes a dead stop, so that f is infinite and $1/f = 0$. Cases like these occur when objects accidentally get on the lane, such as a deer crossing or a container falling from a truck. Table 9 contains four example parameter combinations, and Figure 13 contains a plot for the capacity results, in km's and hours, all assuming $TR = 1$ sec. The first three cases are for passenger cars only, of length L = 4 meters. The last column contains more realistic values for braking performance of 5.5 m/s^2 for cars and 4.8 m/s^2 for trucks, and it is assumed that the average vehicle length is 8 meters.

Table 9: Some combinations of brake accelerations

brake acc. \ case	*1*	*2*	*3*	*4*
f	∞	6	5	5.5
b	5	5	5	4.8
L	4	4	4	8
optimal speed (km/h)	22.7	55.8	∞	88.4
optimal capacity (vehicles/h)	1589	2374	∞	2180

Figure 13: Capacity profiles



The optimal speed can be found by taking the derivative of the capacity and setting it to zero. The derivative can be found a bit quicker by first dividing the numerator and denominator in the capacity expression by *v*, giving:

$$Capacity = \frac{1}{TR + \frac{1}{2}\, v\,(1/b - 1/f) + L/v}$$

$$\frac{\partial\, Capacity}{\partial v} = -\frac{\frac{1}{2}\,(1/b - 1/f) - L/v^2}{(TR + \frac{1}{2}\, v\,(1/b - 1/f) + L/v)^2}$$

$$\frac{\partial\, Capacity}{\partial v} = 0 \quad \Rightarrow \quad v = \sqrt{\frac{2L}{1/b - 1/f}}$$

Substituting this optimal speed into the capacity relation then gives optimal capacity.

A bit to one's surprise, perhaps, the optimal speed depends crucially upon the average length of the vehicles. This should be more obvious at slow speeds, when vehicles can drive close to one another. At higher speeds, when the distances between the vehicles can be much larger than their average length, the length of the vehicles might seem less relevant. For example in above example with a safety distance of 45 m and a braking distance of 90 m, the vehicle length of 4 m indeed is a mere 8.8 % of the safety distance or a 4.4 % of the braking distance. However, at higher speeds, the same algebra stands.

Another result is that the reaction time has no effect on the optimal speed, but only on the optimal capacity.

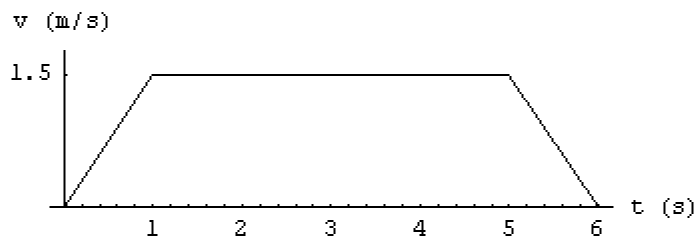
Note that these relationships change when the assumptions are changed. For example, braking accelerations can be made dependent upon the reaction time, and notably $b = b(TR)$. When a backtrailer is not sure whether he or she should stop, a

first reaction may be only a slight brake, and after a while when it fully dawns on the driver that a full stop must be made, then the maximal brake acceleration applies. In that case the mathematics of the problem clearly are a bit more complicated. We abstain from developing these issues.

Example questions

(1) An elevator moves to an upper floor according to the *v* & *t* plot in Figure 14. Give the total height lifted.

Figure 14: Elevator



(2) Regard the situation when a frontrunner car brakes, and a backtrailer car has to stop in order to prevent a collision. It is assumed that there is only one lane, without the possibility to go sideways.

The vehicles have length L meter and drive at speed v m/s. The safe driving distance between the vehicles is S m. The frontrunner brakes with $-f$ m/s^2, the backtrailer has a reaction time of TR seconds, and then brakes with $-b$ m/s^2.

(a) Deduce that $S = v\ TR + ½\ v^2\ (1/b - 1/f)$.
(b) Scetch the road capacity profile over the range of 0 till 200 km/hour for $L = 4$, $TR = 1$, $f = 5.5$ and $b = 4.8$
(c) What is the optimal road capacity given these parameter values ?
(d) From a point of road safety, how would you criticise the assumption $f = 5.5$?

5. Elementary Newtonian Mechanics

Forces

The force on an object is defined as its *mass* times its *acceleration*:

$$\Sigma F = m \ a$$

Gravitational pull between two objects with mass m and m' is given by

$$G(m,m', r) = \gamma m \, m' / r^2$$

where r is the distance between the objects and where γ (gamma) is the gravitational constant.

We can substitute the values $m' = m_E$ for the mass of Earth and $r = r_E$ for the radius at sea level, and then find Earth's gravitational acceleration $g = \gamma m_E / r_E{}^2 =$ 9.8 [m / s^2], so that

$$G(m) = m \ g$$

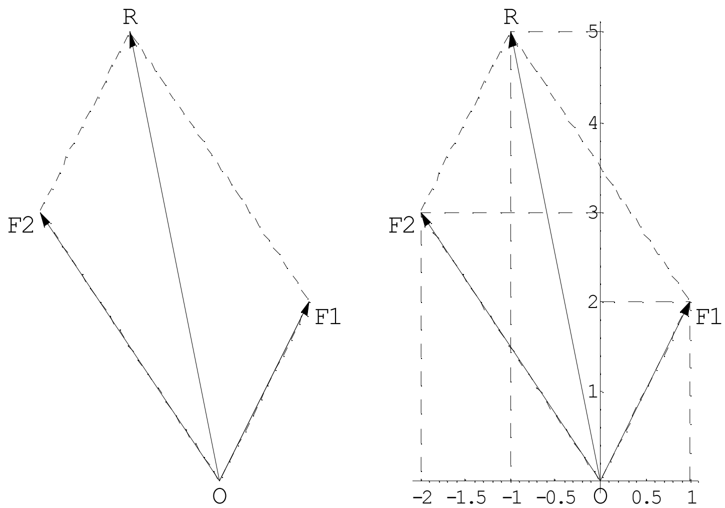
Table 10 reviews this derivation.

Table 10: Gravitational constant and Earth's acceleration

Concept	*Symbol*	*Value*
Earth mass	m_E	$5.997 \ 10^{24}$ kg
Earth radius	r_E	6378.45 km
gravitational constant	γ	$6.67 \ 10^{-11}$ m^3 / (kg s^2)
Earth's acceleration	$g = \gamma m_E / r_E^2$	9.831 m / s^2 at the poles

Forces also have *directions*. Figure 15 shows how two forces can be added. When force F_1 is given as $\{x_1, y_1\}$ and F_2 is given as $\{x_2, y_2\}$, then the resultant R is given as $\{x_1 + x_2, y_1 + y_2\}$. This gives the following hint: When doing sums on resultant forces, it often is a good idea to decompose them in such Fx and Fy values.

Figure 15: Addition of two forces



A body can only be at rest when all forces cancel each other. By consequence of the properties of addition of forces, this cancelling also holds in de different dimensions. Thus for the two-dimensional plane, an object experiences no net force when:

$$\Sigma F_x = 0, \quad \Sigma F_y = 0$$

Forces are often given in polar form, thus as $\{r, \alpha\}$ with $r = m\ a$ the absolute value of the force in the direction of the force itself, and α the angle of the force with the horizontal plane. Then one can find the Cartesian co-ordinates as $\{x, y\} = \{r \cos(\alpha), r \sin(\alpha)\}$.

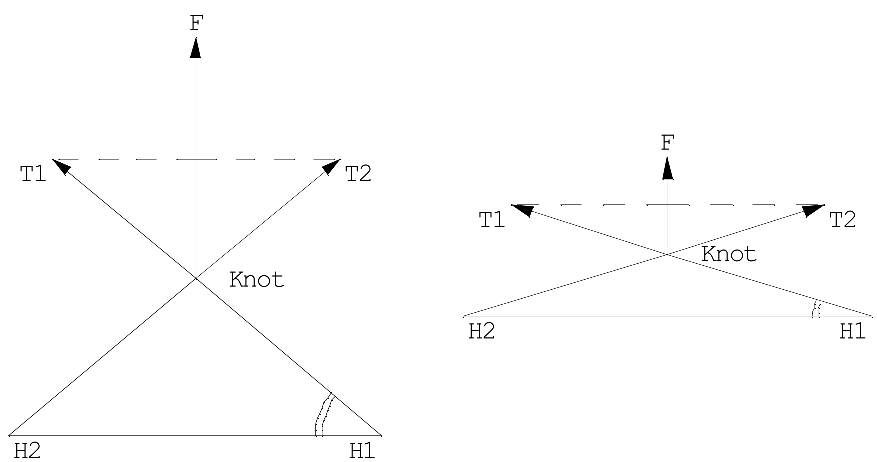
Conversely, when the Cartesian co-ordinates $\{x, y\}$ are given, then the polar form can be found by Pythagoras's Theorem, as $\{\sqrt{x^2 + y^2}, \arctan(y / x)\}$.

Lifting objects

Another example of the composition of forces concerns the lifting of objects. Regard a container and fix a rope to the points H1 to the right and H2 to the left. These ropes are knotted in the middle, effectively making a ‘split rope’. Then the container is lifted at this knot. The situation is depicted in Figure 16. (With heavy loads and thick cables, the length of the cable adds to the mass lifted, and the following computation becomes a crucial element in engineering.)

The lift causes the split rope to make an angle α with the horizontal plane, which angle is arced in the figure. The lifting force F has to be distributed along the split rope, causing subvectors $T1$ and $T2$. Since $T1$ and $T2$ are of the same absolute size T, and since adding them again gives F, it follows that their projection on the y-axis is at ½ F. It follows that $\sin(\alpha) = ½\, F / T$, or $T = ½\, F / \sin(\alpha)$. Thus, the force along the split rope is larger (smaller) than the original lifting force F when ½ is larger (smaller) than $\sin(\alpha)$, i.e. when α is smaller (larger) than .52 rad.

Figure 16: Forces on a split rope

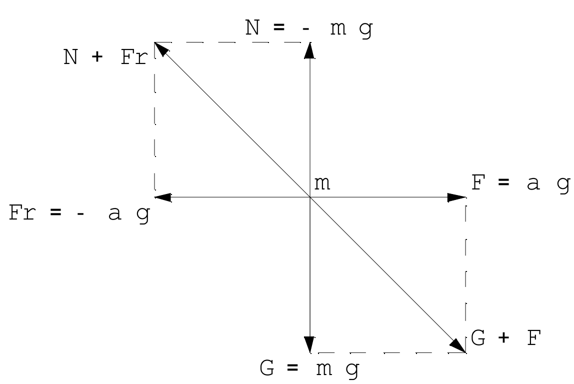


Often, a force meets a frictional counterforce, and the resultant acceleration is zero. In that case we clearly distinguish between the original forces, and the resultant. This distinction even helps in defining the size of friction.

Figure 17 contains a diagram of the forces involved with friction on a flat surface. First of all, there is the gravity *G* pulling mass *m* downwards, and the 'normal' force *N* created by the surface pushing the object back. A force *F* pushing the object to the right meets friction *Fr* counterbalancing it. The resultant forces are $G + F$ and $N + Fr$. The frictional coefficient of the surface can be defined by the *maximal* force F that can be exerted without the object moving:

$$f_0 = Fr_{\mathrm{MAX}} / N$$

Figure 17: Friction on a flat surface



There are two key notions on surface friction:

1) The frictional coefficients depend on the material and the mass of the object, but not on the size of the contact surface (except when the material deforms).
2) The frictional coefficients reduces when the object starts moving. Figure 18 contains a graphical display, and Table 11 contains numerical examples.

Figure 18: Friction depending upon speed

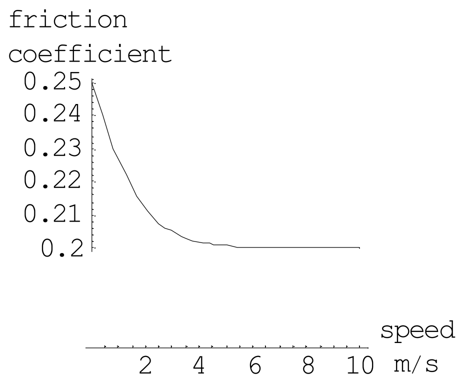


Table 11: Example frictional coefficients

Materials	f_0	f (*for moving mass*)
steel / messing	0.25	0.20
steel / steel	0.30	0.15
steel / teflon	0.05	0.05

Gravity on a slope

A basic example of the directional aspect of forces is given by the effect of gravity on objects on a slope. Figure 19 shows an object with mass m on a slope with angle α with the horizontal plane. Gravity pulls at m with force $G = m\ g$. Gravity creates a force $\cos(\alpha)\ G$ at a right angle with the slope. The slope itself exerts an opposite (so-called 'normal') force N, in this case $N = \cos(\alpha)\ G$. The resultant force is $T = \sin(\alpha)\ G$. For the resultant acceleration along the slope we find $a = T / m$ (so that $T = m\ a$). Hence:

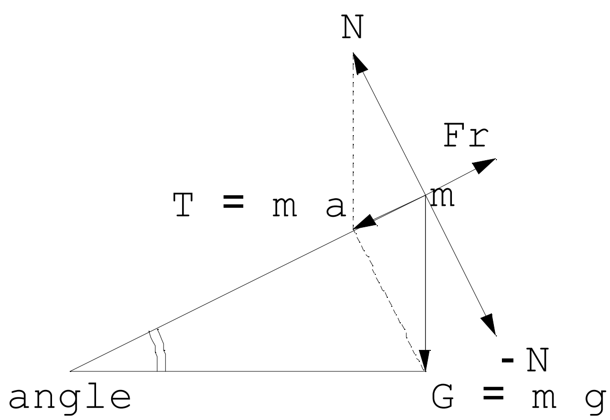
$$a = T / m = \sin(\alpha)\ G / m = \sin(\alpha)\ g$$

The frictional coefficient of the slope is the same as when it were flat. However, the forces are different on a slope, since the slope changes the *direction* of $Fr = T$, see Figure 19. The frictional coefficient can in fact be determined by the following procedure:

a) Put a mass *m* on a horizontal surface.
b) Gently increase the angle α of the surface.
c) Once *m* starts moving, stop changing the angle. Measure this critical angle.
d) The frictional coefficient can be determined by solving:

$$f_0 = \frac{T}{N} = \frac{m\ g \sin(\alpha)}{m\ g\ \cos(\alpha)} = \tan(\alpha)$$

Figure 19: Forces on a slope



Application to bulk storage

In bulk storage of coal or iron ore, the bulk commonly is poured or tipped, creating mountains with slope *f*. Note that the bulk good normally is tipped with a start speed, so we use *f* instead of f_0. The latter is also wise from the viewpoint of safety, since if a granular pile is stored at slope f_0 and it would start moving for some odd cause, e.g. a bird landing on it, there would be an avalanche of huge masses, which would be very dangerous for people working there. Alderton (1995:97) contains a list for the 'angles of repose' implied by friction.

For a conic pile, with radius *r* and height *h*, we find that $f = h / r$. Since *f* has been given as the coefficient for the specific commodity, we can find the radius as a function of the height of the pile as $r = h / f$. With *h* the independent variable, we can find the storage area, its volume, and, with ρ the density (kg / m^3) also the total mass and the pressure exerted on the storage area. This is done in Table 12.

Table 12: Bulk storage in a conic pile

Concept	*Symbol*	*Dimension*	*Remarks*
height	h	m	independent variable
radius	$r = h / f$	m	$f = \tan(\alpha)$ is commodity specific
area	$A = \pi r^2$	m^2	
volume	$V = 1/3\ \pi r^2 h$	m^3	
mass	$m = 1/3\ \pi r^2 h \rho$	kg	ρ is the commodity specific density
average pressure	$p = 1/3\ h \rho g$	N / m^2	a Newton is $N = kg\ m / s^2$
peak pressure	$p^* = h \rho g$	N / m^2	at the center of the surface

Another kind of granular bulk storage concerns the silo. The silo has a conic tip, so that the bulk can easily flow out. One of the physics surprises of this kind of storage is that sometimes the bulk forms a 'bridge' that prevents outflow. Thus, even when the hatch is open, and there is a load in the silo, still nothing flows out. The small grains form a 'Roman arc' that is stable and that appears capable of bearing the masses on top of it (that also form these arcs). In the past, some people have tried to start the material flow again, by trying to break that bridge by stirring it with a stick. This appeared to be troublesome, since both the bridge did not always give way, and, when it did, the stored massed flowed all at once, causing the silo to crash and burrying these physics experimenters. The more common solution today is to design the silos in such manner that these bridges are no longer formed.

Example questions

Question 1: Addition of forces, 1 kg

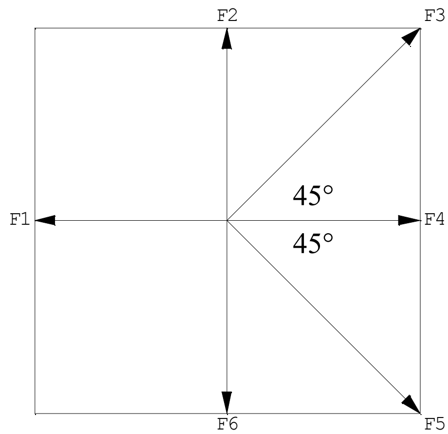
Six forces work on a mass of 1 kg. These forces are drawn in Figure 20, with the mass in the center. There is the following information:

1) F1 = F2 = F4 = F6 = 4 N (these forces are perpendicular)
2) F3 = F5 (with F3 45° and F5 -45° with the horizontal axis).

The questions are:

(a) In what direction and at what angle with the horizontal axis will the mass move?
(b) What will be its acceleration ?

Figure 20: Six forces



Question 2: Elevator

Go back to chapter 4 question 1, on the elevator. The elevator holds a person of 80 kg. Gravitational acceleration is 10 m/s^2. The floor exerts a force F^* on that person. Give the minimal and maximal values of F^*, and draw a graph of F^* as a function of time.

Question 3: Addition of forces, 1000 N

Let a 1000 N load hang on a ring, and let the ring be fixed to two ropes that are attached to a left wall and a right wall. The rope to the left makes an angle of 45 degrees with the wall, and the rope to the right makes an angle of 60 degrees with the wall. Find the tensions in the two ropes. See Figure 21.

Figure 21: 1000 N on two ropes

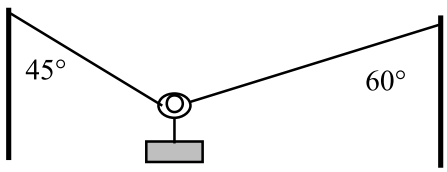
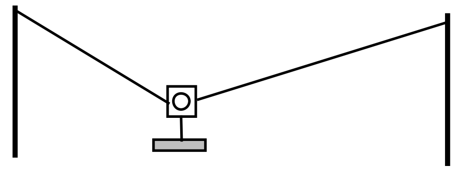


Figure 22: 100 kg on one rope



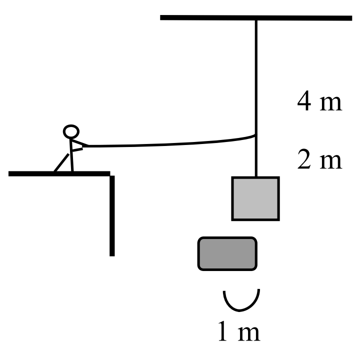
Question 4: Another addition of forces, 100 kg

Let a 100 kg load hang on a pulley on a rope that is 6 meters long. The pully can slide across the rope. The rope is affixed to two walls that are 4 meters apart. Calculate the tension in the rope, using $g = 9.81$ m / s^2. See Figure 22, and note that the ropes need not be affixed at equal heights.

Question 5: Another addition of forces, 50 kg

A crate of 50 kg hangs on a ceiling, and has to be moved 1 meter to the left in order to drop it onto a cart. A horizontal rope is affixed to the vertical rope, with 4 meters from the ceiling and 2 meters from the center of gravity of the crate. What force must be exerted on that horizontal rope? See Figure 23.

Figure 23: 50 kg on one rope

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6. Volume and Mass Flows

Definitions

Definition: The **volumetric mass** (density) of a material is given as the mass of the volume of 1 m^3 of that material.

Thus: With mass *m* and volume *V*, the volumetric mass is $\rho = m / V$, and its dimension is kg per cube (kg / m^3).

Example: Water has a volumetric mass of 1000 kg / m^3 . This in fact caused the definition of a tonne, with one volume-tonne of water weighing one tonne of mass. Iron ore may have a volumetric mass of 3000 kg / m^3, and steel has a volumetric mass of 7800 kg / m^3.

For bulk goods it is of course important how tightly packed the granules are. Normal coal bulk may contain a lot of air, and have a volumetric mass of only 900 kg / m^3. Grinded coal bulk (coal dust) will have a volumetric mass of 1000 kg / m^3 .

Definition: The **volume flow** is given as the change of volume per time interval.

Thus: With *V* the volume, *dV* the change in volume and *dt* the time interval (change in time), then the volume flow is *dV/dt* and its dimension is cube per second (m^3 / s).

Note: The volume is denoted with capital *V*, since lower case *v* is the velocity.

Example: Take a plastic cup, and punch a small hole in the bottom. Put your finger on the hole, and fill the cup with *y* liters of water (using a kitchen measurement tool). Take a stopwatch, and release your finger for 1 second. Then measure what remains in the cup (using that tool). Let this remainder be *x*. Then the volume flow is ($y - x$) liters / s.

Definition: The **mass flow** is given as the change (passage) of mass per time interval.

Thus: With *m* the mass, *dm* the change (passage) in mass and *dt* the time interval (change in time), then the mass flow is *dm/dt* and its dimension is kilogram per second (kg / s).

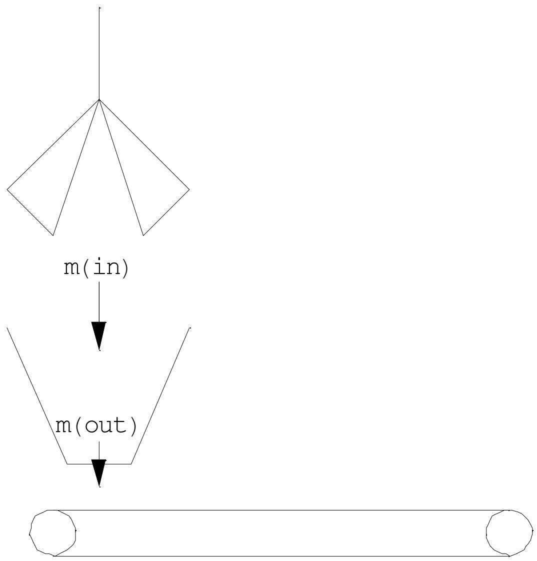
Note: Sometimes the density of a material can change, notably when pressure is applied. However, we normally assume that the density is given, and then:

$$dm/dt = \rho \; dV/dt \qquad \text{(with: kg / s = kg / m}^3 \text{ * m}^3 \text{ / s)}$$

Regard a bulk good with a density of ρ = 1000 kg / m^3. This bulk good is transshipped by a crane grab with a content of 9 cube and thus a carrying mass of 9000 kg.

Loading and unloading of the grab is a discontinuous process, with huge quantities involved. However, we wish to transport the bulk good to a plant or storage facility that needs a continuous supply of normal quantities. It will clearly not do to unload the grab in one single movement onto a conveyer belt, since the conveyer belt will be burried and break down under the huge load. So we install a bunker inbetween. This also has the advantage that we can add a measuring and weighing device, so that we know how much is unloaded from the grab and put onto the belt. Figure 24 gives a graphical outline of the whole setup, and also shows that the mass inflow is different from the mass outflow. [14]

Figure 24: From grab to bunker to belt



1) Due to the cost of shiptime, the unloading of the ship is the dominant factor. The grab cycle period is 45 seconds, which means that there are 80 cycles per hour.
2) Thus, also, the grab supply is 9 t / cycle =9000 kg / 45 s = 200 kg / s = 720 t / h

[14] See also the inventory models in Krajewski & Ritzman (1999) or Anderson c.s. (1999).

3) To prevent an overflow of the bunker, the average outgoing mass flow must be at least as fast as the average mass outflow, so we let the belt run at *dm(out) / dt* = 200 kg / s.

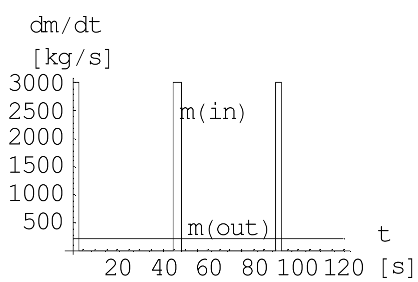
4) Opening of the grab takes 3 seconds, which means that the load of 9000 kg leaves the grab and falls into the bunker in 3 seconds. Hence *dm(in) / dt* = 9000 kg / 3 s = 3000 kg /s.

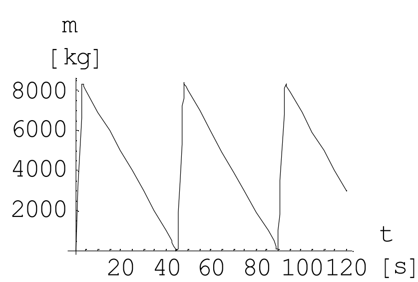
5) Figure 25 (left) contains a diagram of the inflow and outflow. Note the cycle period of 45 seconds, and the amplitude of the cycle of 3000 kg / s. The amplitude lasts for 3 seconds. In those 3 seconds, outflow is only 3 * 200 = 600 kg /s. A picture like this always means that there is a buffer somewhere.

6) The size of the buffer must be at least 3*3000 - 3*200 = 8400 kg. With ρ = 1000 kg / m^3 this means a volume of 8.4 m^3.

7) We complete the analysis by also denoting the mass in the bunker as a function of the cycle. This function will have a sawtooth shape. With *m(t)* the mass in the bunker in kg at cycle moment *t,* then *m(t)* = 8400 for $0 \leq t \leq 3$ when grab inflow replaces belt outflow, and *m(t)* = 9000 - 200 *t* for *t* > 3 when there is only an outflow. This function is depicted in Figure 25 (right). The slope of the sawtooth is *dm(out) /dt* (with a negative sign).

Figure 25: Mass flow (left) and storage (right)





These results allow some preliminary conclusions:

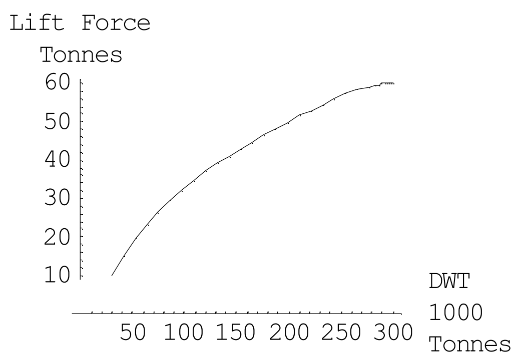
- The cycle period of a *discontinuous* mechanism is determined (a) by physical properties of huge masses that are subjected to large accelerations, and (b) by the proficiency of the crane driver dealing with these forces.
- The cycle period of a *continuous* mechanism is determined by its speed.
- Continuous mechanisms tend to require less volumes per second and thus are more favourable in the demands on size and strength of the construction.
- For vertical movements, discontinuous mechanisms have a design advantage, since there are far less moving parts.

However, these are just preliminary conclusions, and there are also other considerations to take into account.

Limits to grab

Long ago, between 1945 and 1975, there was an almost linear increase in the sizes of cranes and the lift forces and cycle times of their grabs. However, when compared to the ship sizes, the development was more curved. Larger ships require larger distances of movement, and this affects performance. Part of the experience also was that it was better to have larger cranes and grabs instead of simply more. Figure 26 then plots the observed average link between dwt's and grab lift forces. The conclusion is suggested that grabs are reaching a limit in their performance. Physics indeed shows that strains on the crane bridge, cables etc. are getting huge. Also, manoeuvring gets more complicated, with larger risks of damage to ship and grab itself.

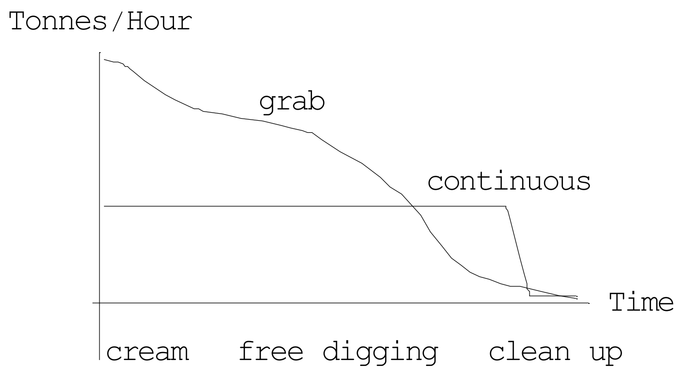
Figure 26: Crane grab lift force as a function of ship's dwt



Digging efficiency

Digging with a grab has distinct characteristics. At first the digging is most easy, and this is called the 'cream digging' phase where the grab reaches its highest performance in tonnes per hour. Then there is period during which the digging still is relatively easy, but not as quick; this is called the 'free digging' phase. Finally, the free digging phase tends to end abruptly, and there is a longer and much slower 'clean up' or 'trimming' phase. Figure 27 contains a plot of these phases. The figure also contains a profile for continuous unloading machines. These latter machines have a continuous flow, and they can better reach into the sides of the ship so that their clean up phase is much shorter. Note: the axes contain no numbers, since we only plot profiles.

Figure 27: Phases in digging



Note that the digging phases are defined by the specific angles of repose. Digging a hole causes the sides to slide to the middle of that hole. We discussed this slope *f* above.

Table 13 contains some key numbers for a big grab. The cream digging phase may be 120% of the free digging phase. Because of clean up, the average performance may be only 50% of the free digging phase. This latter number is called the 'efficiency' of the crane-grab combination. Thus, the efficiency of the system is its average performance, expressed as a percentage of the performance in the free digging phase.

Table 13: Digging phases

state of the system	*tonnes / hour*	*in % of the free digging phase*
cream digging phase	2400	120 %
free digging phase	2000	100 %
average	1000	50 %

For a big ship the cream digging phase lasts long enough to take advantage of it. This means that the crane and grab are designed for top performance, at 120% of the free digging phase. This however means that machines and materials are designed for huge strains, which is expensive, and that there is a basic 'overcapacity' for long periods of time. Note too that crane producers may advertise the cream performance of their cranes, but the operations manager should be aware of the average performance in actual use.

Because of the huge crane sizes, crane designers have become much more critical of their designs. Airplane designers already know by heart that each 90 kg saved in materials allows the addition of one passenger, and crane designers are currently adopting that attitude.

Continuous alternatives

Designers are looking into continuous alternatives for crane-crab combinations because of their favourable operating characteristics.

One alternative is the pneumantic approach. In this case the bulk is sucked into a pipe and transported to a conveyer belt. It appears that this only works well with relatively light bulk goods. This method is very energy intensive, but energy only is a small percentage of costs.

Another alternative is the hydraulic approach. Regard the example of coal transport from the coal mines of China or South Afrika to Rotterdam. It used to be the situation that this coal was grinded and homogenised in Rotterdam before it was offered to the furnaces of the Rotterdam power plant. Grinding the coal at the mines already would introduce a transport advantage, since the density of coal dust is much larger than the density of coal chunks. Secondly, that coal dust could be put into a solutant, creating a sludge that allows hydraulic methods for transshipment. That solutant might be water, but also oil, since the material will be burned anyway. However, the use of water may be the most common approach, due to the readily availability of water. Indeed, such a sludge approach has been tried in Canada. It appeared to be rather expensive, and it came with the problem of water pollution. With energy prices expected to rise in the future, the sludge approach may be promising, especially when furnaces are adapted to coal / oil combinations. Note however that the list of problems is not exhausted yet. The current method of supplying dry coal allows storage in piles, and the energy plant has a distinct ‘reclaiming strategy’ for mixing various coal types into the proper mixture for burning. If instead tankers of coal sludge would be supplied, then storage tanks would have to be built, and the mixing would become a different type of process.

A final alternative is the mechanic approach. This still allows for various solution methods. One possibility is to equip a wheel or a conveyer belt with small buckets that grab into the bulk. Another possibility is to use a screwlike tool. Again another method is a sandwichbelt, where the material is pressed between two belts that lift it.

The basic property of the mechanical approach is the friction between the tool and the bulk material. Presently, iron ore cannot usefully be transshipped in this manner, due to this friction.

A useful requirement for these mechanic approaches is that there is a hull around the process. This both provides a fixture for the various parts, and protects against noise, dust and spillover. This hull however might also cause additional friction. So the design challenge is to balance such friction with the advantages of the continuous flow itself.

In principle some of these methods could be so flexible that the machine operator can actually stand on the ship itself, and operate the machine using a small joystick.

An example of the performance of a bucket elevator are the following data. A hull has a diameter of 50 centimeters, and the buckets move at a speed of 2 - 3 m/s or 750 - 2000 t/h.

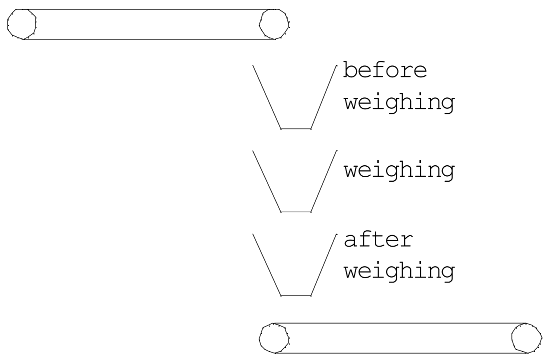
Continuous disadvantages

A disadvantage of continuous methods like a conveyer belt is that it is difficult to measure the actual mass flow. The mass is continuously in movement, and the accelerations and girations hinder a precise measurement. But the transshipper still wants to know how much is being transshipped, or how much was actually in the ship for which he will sign a transshipment bill. The basic idea of weighing then is that the continuous movement is temporarily changed into a discontinuous movement.

The latter might be done straightforwardly, by setting the conveyer belt to a stop. However, this causes a number of problem. It means that the ship is not unloaded as fast as could be done, and that costs money. Also, starting a conveyer belt with all its mass on top is bad for the equipment and costs more electricity than simply continuing its speed, and the power company puts a fine on such peak load use, of EUR 5,000 per occasion.

To solve this weighing problem, the engineers have invented the weighing contraption depicted in Figure 28. The change of continuous to discontinuous movement necessarily implies some storage somewhere, and the figure therefor contains some buffers. The weighing buffer is put in the middle, and there the mass can be at rest for a while, to be orderly weighed. Once weighed, the weighing buffer empties into a buffer below it. Once the weighing buffer is empty, its hatch closes, and the buffer on top starts pouring into the weighing buffer. All the while, the conveyer belt on top empties into the top buffer, and the bottom buffer empties onto the bottom conveyer belt, so that there indeed is no interruption of the continuous flow as such.

Figure 28: A weighing buffer contraption



Another disadvantage of continuous methods is that not all subsequent processes necessarily are continuous too. So, with a continuous inflow arriving at a spot without continuous outflow, there occurs spontaneous piling and storage. There will be costs involved with dealing with such piling properly.

An example in case is the Siwertell machine in Amsterdam harbour that is used for ‘agri bulk’. Its intention is to transship from short sea vessels into barges. The method is continuous, and the flow is created by a screwlike mouth that feeds from the ship’s bulk. The weighing contraption above is in fact used, in a tower of about ten meters high. The flow is 750 t/h, and with a maximal buffer mass of 150 tonnes (for a single buffer in the weighing contraption), it follows that the maximal rest period is 150 / 750 = 1/5 hour or 12 minutes.

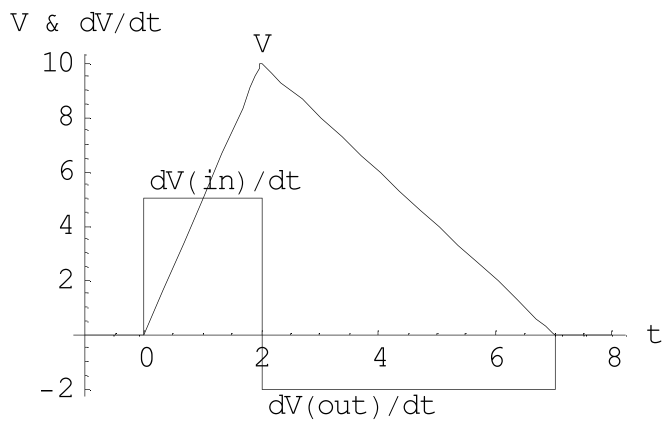
In the Siwertell case they have tried to combine the weighing process with the changeover of barges. The engineers presumed that it should be possible to replace a full barge with an empty barge within 12 minutes. This however appeared to be less practical, and now they are redesigning the construction, at additional costs.

Figure 29 helps to understand the complications of the situation. Let maximal storage be *Vmax*. Let inventory be *V*, its change *dV/dt.* Let the buffer size be *Vmax* = 10 and let us regard *v*(in) = 5 and *v*(out) = 7. When the buffer is empty and open, then “*v*(out)” = *v*(in), since there can go out only as much as goes in. Hence, the net inflow *dV/dt* = 0. At *t* = 0 the buffer hatch is closed, and then *dV/dt* = *v*(in). The volume stored in the buffer is *v*(in) *t* until the moment is reached that the buffer is full, which is at *t** = *Vmax* / *v*(in). Then the hatch is opened, and there starts an outflow out of the buffer. In principle *v*(out) > *v*(in), but since the inflow continues, the net outflow is only *dV/dt* = *v*(in) - *v*(out) (which has a negative sign). We see that it takes longer to empty the buffer than to fill it, even though *v*(out) > *v*(in).

When it takes long to empty the buffer, then the barge downstream is stuck there, since it must remain in place to receive that stream. If the buffer could be emptied

much quicker, then there would be more time to replace the barge downstream. But note that we already have the situation that v(out) > v(in), so that already more demands are placed on the outgoing stream. We must clearly distinguish between the outflow v(out) for the conveyer belt and the net outflow of the buffer v(in) - v(out). It is the latter that is causing the problem, and it is a problem that will not go away so easily.

Figure 29: Buffer, inflow and outflow



Formulas for discontinuous/continuous conversion

Above we gave an example how the discontinuous mass flow of a grab translates into the continuous mass flow of a conveyer belt. This example used numbers, and was not in a general mathematical format. Presently we will use the latter format.

We approximate the (instantaneous) volume flows (i.e. the derivatives) as the average flows: $dV/dt = V / T$. We are here interested in the averages anyway.

Grab volume flow, payload and deadweight

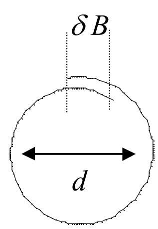
Let a grab have a deadweight of DW and a payload of PL, then the total gross weight is $TGW = DW + PL$. Normally the crane measures the TGW rather than the payload. Let the payload deadweight ratio be $k = PL / DW$. Then $PL = TGW\, k / (1 + k)$. With $PL = \rho\, V$ and the volume flow as a constant average, then:

$$dV_d / dt = \frac{V}{T_d} = \frac{PL}{\rho \ T_d} = \frac{k}{1+k} . \frac{TGW}{\rho T_d}$$

Volume flow in a pipe belt elevator

Let a pipe belt have a width of B.[15] When rolled to a pipe, the overlap is δB and the crosssection diameter is d $(= 2 r)$. In that case, the circumference is πd, and $B = \pi d + \delta B$. Note that the overlap is counted correctly, see Figure 30. Hence $d = (1 - \delta) B / \pi$.

Figure 30: Crosssection of a pipe belt elevator



The crosssection surface is $\pi r^2 = \pi / 4 \ d^2$. When the belt moves at speed v, the volume flow is:

$$dV_c / dt = \frac{\pi}{4}\left(\frac{(1-\delta)B}{\pi}\right)^2 v = \frac{(1-\delta)^2}{4\pi} B^2 \ v$$

[15] Belt widths are expressed in millimeters.

The volume flow in a disc elevator

A 'disc elevator' can be seen as a normal elevator, as in every modern large building, but then with many discs following one another. Two discs actually form a 'cubicle'. As soon as one cubicle disappears, the next appears. The string of cubicles turns upside down on the way down, to make a continuous flow into one direction (but up and down). Also, suppose that the cubicles are real cubes with side R, then volume is R^3. Let the disc elevator move with v [m/s], then we can define $T_c = R / v$. Then the volume flow is:

$$V_c / T_c = R^3 \; v / R = v\, R^2$$

Equating volume flows

We use V_d for the volume in discontinuous movement and V_c for the volume in continuous flow. Volume flow follows from dV/dt, and smooth conversion means that $dV_d / dt = dV_c / dt$. Here we are interested in averages. These averages can also be determined using different time periods, that is, we can use period T_d to measure the average of the discontinuous method, and we can use T_c to measure the average for the continuous method. Making the volume flows equal, allows to solve unknown variables.

Let us regard an example for the disc elevator:

$$V_d / T_d = V_c / T_c$$

$$R = \sqrt{(V_d \;/\; T_d) \;/\; v}$$

For example, if $v = 2$ m/s, $V_d = 25$ m^3 and with $T_d = 45$ s, we find $R \approx 0.5$ m.

There are two major conclusions. The first is that if speed is larger, then the cubicles can be made smaller. The second is that a grab volume of 25 m^3 translates as a cube with edges of 2.9 m, while the cubicles of the disc elevator have edges of only 0.5 m. So there is a major reduction in the size of the tools. Though, of course, one would need more cubicles for a disc elevator, the issue is that the mechanical stresses would be much smaller.

Note: when the volume flow is approximated as $V(T) / T$ for $T = R / v$, then the mass flow can be represented as $dm/dt = \rho \;\; V(v/R) \;\; v/R$.

Comparing continuous and discontinuous

Continuous unloading machines have attractive properties:

- high average capacity and manoevrability at much lighter weights and lower material strains
- output in tonne / hour is commonly better targetted at the needs of the whole chain
- for the environment: less noise, less dust
- better energy use (lower kWh / tonne)
- ease of operation, less risks of crashes.

However, there is still little experience with continuous tools, and there are hardly any 'proven designs'.

Example questions

Question 1: Volumetric mass

Regard a flow of 10 liter of water per minute. The volumetric mass (density) of water is 1000 kg per cube. What is the mass flow ?

Question 2: Inflow and outflow

Regard a buffer with capacity V, an inflow of $I = dm(in)/dt$ and an outflow of $O = dm(out)/dt$. At $t = 0$ the buffer is empty and a mass with density ρ starts pouring in. Determine the critical moment when the buffer starts to overflow, using symbols only.

(You may check this by say having a classroom with space for 50 students, 10 arriving each minute and 5 leaving each minute. The classroom is filled in 50 / (10 - 5) = 10 minutes.)

Question 3: Brewery

Your work at brewery. Wheat with a density of 750 kg / m^3 is supplied by river barges, unloaded by a grab and transshipped onto a conveyer belt. The process served by the conveyer belt requires a volume flow of 0.1 m^3 / s or 360 m^3 / hour. A new berth is now being designed, and you are to make the decision how large the grab is going to be. The data on costs and performance are in Table 14.

(a) Give the optimal decision on the size of the grab, and argue this decision.

(b) Give the size of the bunker that sits between the grab and the conveyer belt.

Table 14: Grab cost and performance

Wheat grabs	*Grab 1*	*Grab 2*	*Grab 3*
Cost	\$1 million	\$1.5 million	\$2 million
Gross weight	5 t	7.5 t	10.125 t
Payload deadweight ratio	1.5	1.5	2.0
Cycle period	40 s	60 s	60 s
Grab open period	4 s	3 s	3 s

Question 4: The brewery revisited

The brewery currently stores its wheat in a conic pile in a shed. The shed is 50 by 50 meters wide, 12 meters high, and its floor can carry a 75 [kN / m^2] load. The wheat has a density of 750 kg / m^3 and an angle of repose of 25 degrees, while the conic pile has a maximum height of 10 m. Though the wheat pile is conic (circular at the base), the surrounding space cannot be used since the wheat might become contaminated, and this gives a lot of unused space.

Management considers storing the wheat in a silo, so that floor space could be used for other purposes. This silo would be circular but would have the same volume as the current conic pile. The silo would be constructed on the same foundations, and hence management wants the top pressure of the silo to be the same as the top pressure of the current cone. The silo would have an annual cost of \$ 1 million, including the construction annuity and more complex maintenance. The brewery attaches a value of \$ 500 / m^2 per year to the useful space that would become available by changing from the current storage to the silo. You can neglect the width of the walls of the silo. And use $g = 9.81$ m / s^2.

(a) What is the current real maximal pressure of the conic pile (that also will apply for the silo).

(b) What is the current volume of the pile ?

(c) What will be the height of the silo ?

(d) What is the area saved ?

(e) Will the brewery put up the silo ?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7. Energy

Work

The definition of *work* is $W = F\,x$, with x the distance over which the force is exerted. Work is measured in Joules, [J] = [N m].

We must take account of the fact that the force may operate at an angle α of the distance traversed. The **proper formula** then is $W = F\,x \cos(\alpha)$. A force that is opposed to the direction of movement, such as friction, thus performs negative work.

A clear example of work is when an object with mass m falls from a height of h. In that case the gravitational force is $G = m\,g$, and gravity performs its work over a distance h, so $W = m\,g\,h$.

Work is a kind of energy.

Power

When we compare a powerful machine with a less powerful machine, then we know that both machines can do the same work, if only the last machine is allowed more time to do it. The work done by a small battery clock, of moving the hands around over the course of many years, could be the same as done in a few seconds by a human who lifts a heavy book from the table to the top of a bookcase.

We find that power is the work per second. Since work is a form of energy, another word for 'power' is 'flow of energy'.

Hence: power is $P = work\,/\,period = W / t$, and it is measured in [Watt] = [Joule / second], or [W] = [J / s].

By consequence, we find that $P = W / t = F\,d / t = F\,v$.

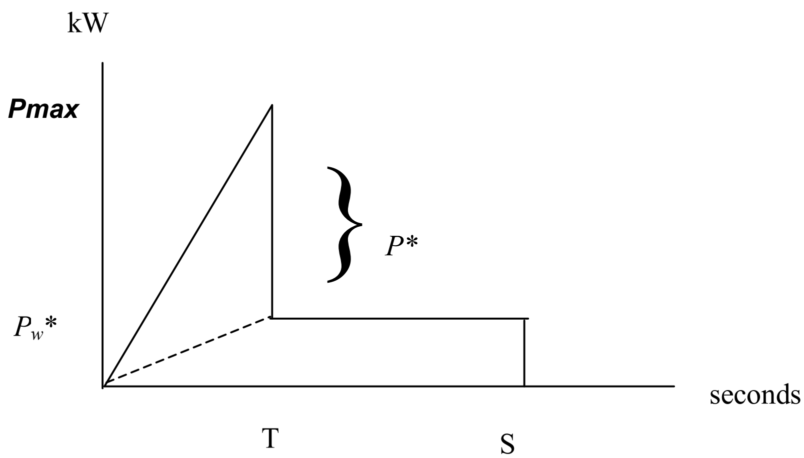
Regard the situation in a harbour when a crane is moved to another ship. Let us suppose that the crane is moved first, for a period T, with a constant acceleration a from speed $v = 0$ till $v = v^*$, and then continues with this constant v^*. At a moment S the motor is turned off, and the machinist can start braking. We are now interested in how much power the motor has to have. (Perhaps it is better not to have a moving crane, and move the ships…)

The crane has mass m. We assume a constant friction coefficient of steel wheels on steel rails of f = 2% (and we thus neglect that friction is reduced for moving objects). We then find:

- Friction causes $F_w = f\,G = f\,m\,g$. This friction is constant and exists during the whole trip.
- The energy flow for overcoming friction is $P_w = v\,F_w$ where v goes from 0 till v^*. This thus is valid for time t = 0 till t = S. This flow rises till t = T to a maximum P_w^* and thereafter stays at this maximal value.
- The force just to increase speed is $F = m\,a$. This is only valid for time t = 0 till t = T.
- The energy flow just to increase speed is $P = m\,a\,v$, thus for time t = 0 till t = T. The maximum P^* is reached at T when speed is v^*.

The situation is depicted in Figure 31.

Figure 31: Energy flow diagram



In a realistic example, let us take T = 5 seconds and a = 0.1 m / s^2 , so that v^* = 0.5 m / s. Also take g = 10 m / s^2. Then P_w = 0.02 * 10 $m\,v$, and P = 0.1 $m\,v$, so that P = 0.5 P_w. Total power thus is 1.5 P_w. This also means that the maximal power at the end of the acceleration period must be 1.5 higher than the power during the period of constant speed.

This also explains why car drivers speak so much about the acceleration 'power' of their cars.

Work is power over some period

Above example of the clock moving the hands over the course of many years, already clarifies that we look at the work content. Clearly, if we multiply P with a period t, we get work again, as $W = P * t$.

A kiloWatt-hour (kWh) is the work that can be done over an hour by a machine with a power of 1000 Watt. Clearly, a power of 1000 J/s applied over 3600 seconds gives: kWh = $3.6\ 10^6$ N m.

When we compare our natural resources like oil, coal or natural gas, then we are interested in how much work we can do with them. Their energy content is measured in kW / tonne. Note that this is more a chemical rather than a mechanical concept. Also, the efficiency of energy extraction depends upon the state of technology.

Kinetic energy

A body in motion has kinetic energy. We can determine the energy by exerting a constant force on it and measuring the distance that it takes to put the body to a full stop.

Table 15: Derivation of kinetic energy

Speed	*Location*	*Work*
$v(t) = v(0) + a\ t$	$s(0) = v(0)\ t + ½\ a\ t^2$	$W = x\ F$
$0 = v - F/m\ t$	$x = v\ (mv/F) - ½\ F/m\ (mv/F)^2$	$W = (½\ m\ v^2 / F)\ F$
$t = m\ v\ /\ F$	$x = ½\ m\ v^2 / F$	$W = ½\ m\ v^2$

With distance $x = s(0) - 0$, $v(0) = v$ and t the time required to stop the body, then $v(t) = 0$, and $a = -F / m$. If we then do the calculations and substitutions in Table 15, we find the formula for kinetic energy $E_k = ½\ m\ v^2$.

Similarly, when a force changes the speed from v_1 to v_2, then the change in kinetic energy is $\Delta E_k = ½\ m\ v_2{}^2 - ½\ m\ v_1{}^2$. One can prove that $\Delta E_k = F\ x$ where x is the distance after which the speed has changed. In other words, the work performed by a constant force on a body, equals the change in kinetic energy of that body.

Potential energy

Above we found the work relating to height as $W = m\, g\, h$. For an object at height h we will call this the potential energy E_p of that object (with respect to $h = 0$).

The potential energy for Earth's gravitational field actually is not constant, since g changes over h. Regard an airplane with mass m at distance r from the center of the earth. Raising the distance from the center from r to $r' = (r + h)$, neglecting air friction and possible changes in speed, will require the energy. The following derivation is for the more advanced readers:

$$W = \int_r^{r'} \gamma \frac{m\, m_E}{r^2}\, dr = \left[-\gamma \frac{m\, m_E}{r} \right]_r^{r'} = \gamma \frac{m\, m_E\, (r' - r)}{r\, r'} \approx g\, m\, h$$

The approximation $W = g\, m\, h$ will hold if $r \approx r_E$ and h is small compared to r_E.

Conservative force fields

A force field is a space in which a body experiences a force at any point of that space.

A conservative force field is a field in which the work performed by the field on a body is independent of the trajectory of the body.

Gravity is an example of a conservative field. Friction is an example of an non-conservative field, since the work performed by friction differs depending upon the trajectory.

Law of conservation of energy

The potential energy of a body in a point A with respect to a point B, all in the same force field, is the work that the force field performs, when the body moves from A to B.

In a conservative force field, the sum of potential and kinetic energy is constant.

The latter is just one instance of the law of conservation of energy.

Impulse

Work is defined as *force * distance*. We can also look at *force * period*. The latter concept is called “impulse”. For example, a soccer player kicking a ball hits that ball only shortly, while the ball moves away very fast. Define impulse $p = F\,t$ and impulse then is measured in [N s]. (Note, sometimes the period is given as Δt.)

When the force considered is constant, then an object with mass m has a constant acceleration. Let t be the period considered, and the speed change from v(0) to v(t). Then:

$$F = m\,a = m\,(v(t) - v(0)) / t$$

$$\Rightarrow \qquad p = F\,t = m\,(v(t) - v(0)) = m\,v(t) - m\,v(0) = \Delta(mv)$$

The value mv can be regarded as the ‘amount of motion’ of a body. The impulse of a force thus is the change of the amount of motion.

There is a law of conservation of impulse. A billiard ball hitting another ball may come to a complete stop, and the other ball will take over its movement precisely. An exploding grenade has the same total amount of motion as before the explosion.

Useful energy, energy loss and efficiency

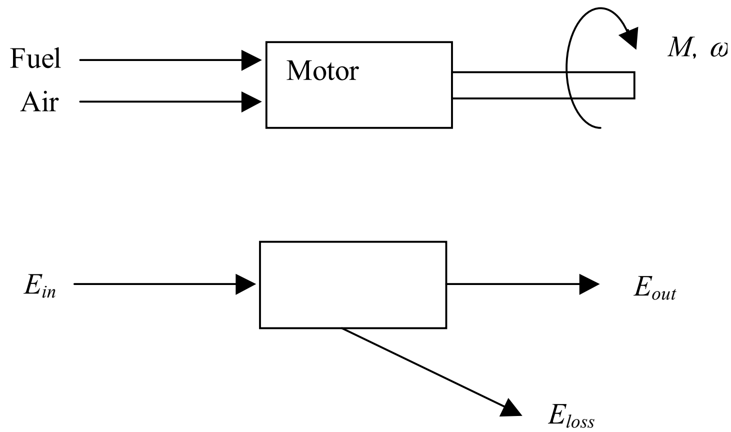
When energy from an available source is transformed into another form of energy that is more useful, then there always will be some loss. This loss is not a loss of energy in itself, since the law of conservation tells us that the amount of energy always stays the same. The loss however is defined in terms of the ‘usefulness’.

Figure 32 depicts a motor that consumes fuel and air and that produces a turning shaft with a certain momentum at angular speed. The energy content of the fuel can be measured, and the rotation of the shaft provides the useful energy. The difference is the loss. This part of the energy is lost as heat and e.g. unburned fuel vapor.

We can measure the efficiency simply as: $\eta = E_{out} / E_{in} = 1 - E_{loss} / E_{in}$.

Note that η is a dimensionless number, and that $0 \le \eta \le 1$, while the value $\eta = 1$ will be achieved only in some theoretical cases but never in practice. For example, a gasoline motor has $\eta = 0.28$, a diesel motor $\eta = 0.45$ and an electrical power plant $\eta = 0.38$. The power plant itself may run more efficient than a gasoline motor, but the whole process of using electricity may be less efficient, since energy is lost by the transport along the electric cables and by the electrical devices.

Figure 32: Efficiency of energy transformation



Energy concepts for vehicles

The ‘specific fuel consumption’ SFC of a vehicle is the fuel consumption per unit propulsion force per hour. The dimension of this concept is kg / (N h).

The ‘specific energy consumption’ SEC of a vehicle is the energy consumption per tonne kilometer. The dimension of this concept is J / (kg m).

The ‘energy efficiency’ is the ratio between the power created and the energy input (the heat value generated by the burning of the the fuel).

The power of a pump

Regard a motor that has to lift a bucket of some fluid 100 meters up. The bucket has no weight.

The question is : What is the energy flow, and can you relate this to the pressure - as when the motor would pump the same volume through a hose ?

Note:

- A column of fluid of $V = h\ A$ and density ρ exerts a force $G = m\ g = \rho\ V\ g$, and the pressure is $p = G / A = \rho\ h\ g$.
- Thus we have P for power or the energy flow, and p for pressure.
- The unit of pressure is the Pascal = N / m^2.
- For example 10 meters under water, the pressure is $p = 10\ 10^3\ 10 = 10^5$ Pascal.

To answer the question, we proceed as follows:

For an arbitrairy fluid: $m = \rho\ V$.

As we have seen earlier: the energy is $W = F\ s = G\ h = m\ g\ h$.

The energy flow is $P = dW / dt = d(m\ g\ h) / dt = g\ h\ (dm / dt) = \rho\ \ g\ h\ (dV / dt)$.

and dm/dt is the mass flow and dV / dt is the volume flow.

If the flow is steady, then these instantaneous flows are equal to the averages, and t would be the time required to lift the bucket.

Let us now look at above formula in terms of its dimensions, and introduce p:

$$P = \underbrace{\underset{\mathrm{kg/m^3}}{\rho}\ \ \underset{\mathrm{m/s^2}}{g}\ \underset{\mathrm{m}}{h}}_{\mathrm{N\,/\,m^2}}\ \ \underset{\mathrm{m^3/s}}{(dV / dt)}\ \ =?=\ \ p\ (dV / dt)$$

where the Newton of course has been defined as N = kg m/s^2. Since the Newton is the dimension of force, we now realise that we have an expression for the force per square meter, or simply pressure.

More accurately, the expression gives the **difference** in pressure between the top and the base of the 100 meters height. With Δ the symbol for a difference, we thus find that $P = \Delta p\ (dV / dt)$.

Example questions

(Q1) Is there a difference between 'power' and 'work', and if so, what is it ?

(Q2) Is there a difference between 'power' and 'energy flow', and if so, what ?

(Q3) How much work does it take to lift an object of 50 kg to a height of 30 cm ? How much work is performed by gravity ?

(Q4) A small aircraft with a total weight of 2.4 tonnes takes off, and gains a height of 4 km in 3 minutes. Give the power of this aircraft.

(Q5) We lift a mass of 2.4 tonnes in 1 minute over a height of 10 meters. What is the energy flow that is required to do this ? Take $g = 10$ m / s^2.

(Q6) A motor pumps 250 liters of water per minute to a height of 24 meters. What are the energy flow and mass flow given by this pump ? Take $g = 10$ m / s^2 and $\rho = 1000$ kg / m^3.

(Q7) A person pushes a cart over a distance of 500 meter. The cart weighs 60 kg, and the roll resistance of the cart is 0.08. Take $g = 10$ m / s^2.

a) Draw a stylized picture with the force lines involved.

b) What is the work ?

(Q8) Prove $\frac{1}{2}\, m\, v_2{}^2 - \frac{1}{2}\, m\, v_1{}^2 = F\, d$ as claimed above.

(Q9) A body with a mass of 10 kg moves along a horizontal plane. In point A its speed is 20 m/s. For the distance AB of 40 m there is a force of 100 N, that makes an angle of 20° with the plane. The coefficient of friction is .25. Give the speed in B, using $g = 9.8$.

(Q10) A Boeing 747 has a payload of 55 tonnes. Its total mass at take off is 350 tonnes, and the average mass during the flight is 310 tonnes. Its cruising speed is Mach .8, or 0.8 * 295 m/s = 236 m/s = 850 km/h. The transport output thus is T_p = 55 * 850 = 46750 tkm / h. We concentrate us now on the cruising flight. A Boeing 747 has a specific energy consumption of 11572 kJ / tkm and an energy efficiency of .32, see Table 16. Compute these variables also for a Concorde.

Table 16: Fuel and energy consumption for Boeing and Concorde

Concept	*Symbol*	*Example Boeing 747*	*Example Concorde*
payload	m_p	55 tonnes	12 tonnes
mass at take off [16]	m_s	350 tonnes	175 tonnes
mass at cruising	m	310 tonnes	160 tonnes
cruising speed	v	0.8 Mach = 0.8 * 295 m/s = 236 m/s = 850 km/h	Mach 2.0 = 2 * 295 = 590 m/s = 2124 km/h ([17])
transport output	T_p	$m_p\, v$ = 55*850 = 46750 tkm/h	
lift at cruising [18]	L	= $g\, m$ = 9.8 * 310	
air lift / drag ratio [19]	L / D	15	7.4
airfriction at cruising	D	L / 15 = 203 kN	
propulsion force [20]	T	= D	
SFC = specific fuel consumption	C_T	0.062 kg / (N h)	0.119 kg / (N h)
cruising fuel consumption	$T\, C_T$	= 203k * 0.062 = 12.586 t/h	
cruising power	P	$T\, v$ = 203*236 = 47908 kW	
heat or caloric value	H	43 10^6 J / kg	equal to Boeing
cruising energy consumption	P_f	= $H\, T\, C_T$ = 43 10^6 J/kg * 12586 kg/h = 541.2 10^9 J/h = 541.2 10^9 /3600 J/s = 150300 kW	
cruising SEC = specific energy consumption	E_s	P_f / T_p = 541.2 10^9 J/h / (46750 tkm/h) = 11572 kJ / tkm	
energy efficiency	η_{TOTAL}	P / P_f = 47908/150300 = 0.32	

[16] Doganis:149 discusses the maximum take off weight (MTOW).
[17] At an altitude of 16 km.
[18] At equilibrium, lift equals gravity.
[19] This ratio remains somewhat constant for different speeds.
[20] At equilibrium, propulsion equals the air friction.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8. Resistance

When a vehicle moves, then there are different forces that resist its movement - and a flow of energy is required to overcome that resistance. Table 17 reviews the various sources.

Table 17: Sources of resistance

Source of resistance	*Symbol*	*Formula*	*Policy angle*
Slope	F_{Slope}	$m\ g\ sin(\alpha)$	Tunnels in mountains, bridges across valleys
Surface contacts ('roll')	F_{Roll}	$f_r\ \ m\ g\ cos(\alpha)$	Modalities, design, materials
Air	F_{Air}	$½\ \rho\ \ A\ c\ v^2$	Aerodynamics
Total resistance	F_w	$F_{Slope}\ + F_{Roll} + F_{Air}$	Reduce *m* or *v* in general

Slope resistance

Of these resistances, the roll and air resistance are 'proper' resistances, i.e. the energy is lost as 'heat'. The slope resistance however increases the potential energy, so that riding back down the slope will be easier, and so that this is no real loss. It is nevertheless useful to include the slope resistance, since it helps us to better understand real events.

Roll resistance

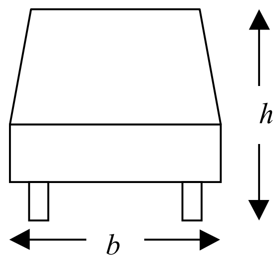
With a car of 1200 kg and a synthetic rubber roll coefficient of f_r = 0.01, the roll resistance on a flat surface is 120 N. Truck tyres of natural rubber have f_r = 0.0058 and trains f_r = 0.001.

Air resistance

In transport economics we saw that the use of fuel was related to the speed, and we discussed the 'cube law'. Presently we are in a better position to understand this phenomenon.

When *b* is the width of a car and *h* its height, then the front of a passenger car is $A \approx 0.8\ b\ h$. Common values are b = 1.8 m and h = 1.6 m, so that $A \approx 2.3$. Figure 33 depicts this measurement.

Figure 33: Front of a passenger car



A cube of air at atmospheric conditions has a mass of about 1.23 kg. The coefficient c or c_w is called the air friction coefficient, and a value for modern passenger cars is $c = 0.28$.

All in all, we find for the air resistance:

$$F_{Air} = ½\ \rho\ A\ c\ v^2 = ½ * 1.23 * 2.3 * 0.28 * v^2 \approx 0.40\ v^2$$

Since the power or energy flow is $P = F\ v$, we find

$$P_{Air} \approx 0.40\ v^3$$

which is the 'cube law' that we were after.

The 'cube law' implies a dramatic influence of speed on energy use. Table 18 gives the result for selected speeds, using above coefficient of 0.40.

Table 18: Higher speed, ever higher force and power

Speed (m/s)	v	10	20	30	40	50	60
Force (N)	F_{Air}	40	160	360	640	1000	1440
Power (W)	P_{Air}	400	3200	10800	25600	50000	86400

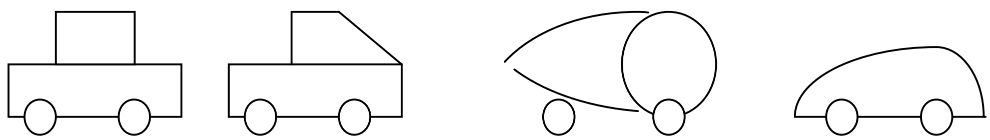
A horsepower is about 0.736 kW. Thus, a speed of 50 m/s or about 180 km/hour requires a horsepower of 50 / .736 = 68 in order to overcome the air resistance.

Ways to overcome air resistance

Engineering on car shapes has resulted into much lower air resistance than traditionally was the case. Some alternative car shapes are depicted in Figure 34. The traditional shape of a car resembled the carriage, with a 'house' stuck onto a carrossery. When motor power increased and higher speeds became feasible, the

slanted windshield was an obvious improvement. The energy crisis in the 1970's prompted experiments in wind tunnels, and the shape of a raindrop was considered as a theorerical shape for a car. Note, though, that if such a car would contain a seated person in the front part, the whole car would need to have a length of 6 - 7 meters. The closest that one has come to the raindrop shape has been with the Tatra, Fiat 850 or Citroen GS in the 1980s.

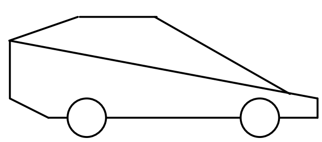
Figure 34: Different car shapes



$c_w = 1.0 - 1.2$ $c_w = 0.8$ *theoretical form* $c_w = 0.55$

Wind tunnel research has resulted into a modern form for cars that is most likely the optimal shape. It has a air resistance coefficient in the 0.28 - 0.30 range. Whereas cars in the 1960s had a performance of 8 - 10 kilometers per liter of gasoline, they now have a performance of 14 - 18 kilometers per liter.

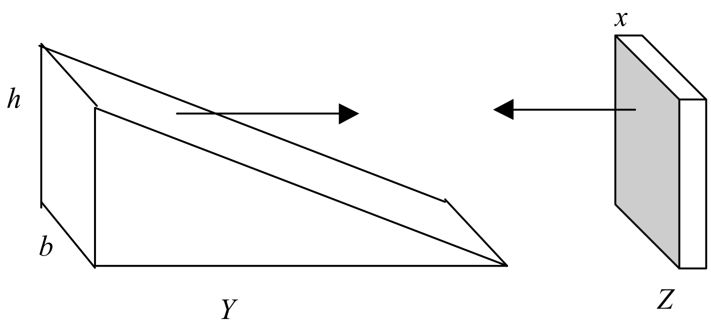
Figure 35: Modern and most likely optimal shape



Derivation of the air resistance formula

Regard a wedge shaped car at position Y approaching a block of air at position Z. This situation is depicted in Figure 36. The car has width b and height h, so a frontal area of $A = b\, h$, which is also the area of of the column of air that we shall be considering. Let this column of air be x meters thick, so the volume is $V = A\, x$.

Figure 36: Car approaching column of air



For our purposes it does not matter if the car moves towards a column of air that is at rest, or if the air moves towards the car that is at rest. The latter approach is easiest when making the physical calculations. These then are as follows:

$$m = \rho V$$
$$dm = \rho \ dV$$

$$V = A x$$

$$F = m a$$
$$dF / dm = a = dv / dt$$
$$dF = dm * (dv / dt)$$

$$dm = \rho A \ dx$$

$$dF = \rho \ A \ dx * (dv / dt)$$
$$dF = \rho \ A \ (dx / dt) * dv$$
$$dF = \rho \ A \ v \, dv$$

$$F = \int dF = \int \rho \ A \ v \, dv$$
$$F = \rho \ A \int v \, dv = \rho \ A \ \tfrac{1}{2} v^2$$

Add a coefficient:

c

$$F = \tfrac{1}{2} \rho \ A \, c \ v^2$$

Collecting all terms, the full formula for resistance is:

$$F_w = m\,g\,sin(\alpha) \;+\; f_r\; m\,g\,cos(\alpha) \;+\; ½\,\rho\;A\,c\,v^2$$

This formula helps us to understand transport policy. The cost of fuel induces us to reduce resistance as much as possible. Little can be done about gravity, but the other factors can be influenced. Table 17 above reviews some of the policy angles.

Some of the policy issues are rather subtle:

- Regard the policy to create separate car lanes with few intersections. In a situation with more intersections, cars have to wait for crossing traffic, and they thereafter increase their speed in order to make up for time lost. But fuel use is related to the maximum speed and less to the average. So, creating car lanes without intersections helps to maintain a high average speed while reducing the maximum speed and thereby saving energy.
- Regard the reason why trains are less useful for freight transport for short distances. Safety requirements cause trains to be constructed with a rather heavy cage. The large mass of the train itself causes a contruction that adds to the mass. One can compare a train with an electric car that runs at much lower speeds, and it then is obvious that the train has been constructed with much more mass. This mass however induces high fuel costs.
- For cars, the frontal area that is so important, has reached the limits of reduction. If the requirement is that two persons should sit next to each other, and if some basic requirements of ergonomics and room to move are to be satisfied, then the area is rather fixed. Some plans have been developed for cars that are ‘one person wide’ but these plans meet with discussions of traffic safety.
- On air resistance, there seem to be few ways to improve on current designs. There are plans to construct vacuum tubes, and have air tight electric trains run through these. These trains might even run at 500 km per hour. The major problems with these plans are of course the construction of the tubes themselves and the air locks that increase handling time and costs.
- Given that other aspects are rather close to their optimal values, it now is explained why the speed of vehicles is a hot discussion item. We already saw that network capacity was highest at rather low speeds, while low speeds also increase traffic safety. Now, we also find that low speeds are useful for energy conservation.

(Q1) Is there a difference between ‘angle’ and ‘slope’, and if so, what is it ?

(Q2) Is there a difference between ‘friction’ and ‘roll resistance’, and if so, what ?

(Q3) A car brakes at a constant acceleration a.

a) Express the braking distance x as a function of the start speed (i.e. the speed of the car at the beginning of the braking) and the coefficient of friction f.

b) Explain why a Anti-Blocking System (ABS) is useful. Thus, explain why braking should not block wheels into a complete stop, but should allow wheels to continue to roll, albeit at a lower speed. In this explanation, you can use the fact that f depends upon the speed.

(Q4) A car has been equiped with an anti-blocking system. The data are m = 1000 kg, g = 10 m / s^2, and v = 20 m / s. The theoretical result of question Q3 is tested in experiments, and the results are plotted in Figure 37. Determine the braking distance.

(Q5) A truck with a mass of 50 tonnes drives on a flat road. Roll friction, air friction and the maximal available propulsion force of the truck are plotted in Figure 38 as a function of its speed.

a) Give the maximal speed of the truck.

b) When the truck drives 20 m / s and then accelerates, what is its maximal acceleration ?

Figure 37: Friction coefficient in different situations

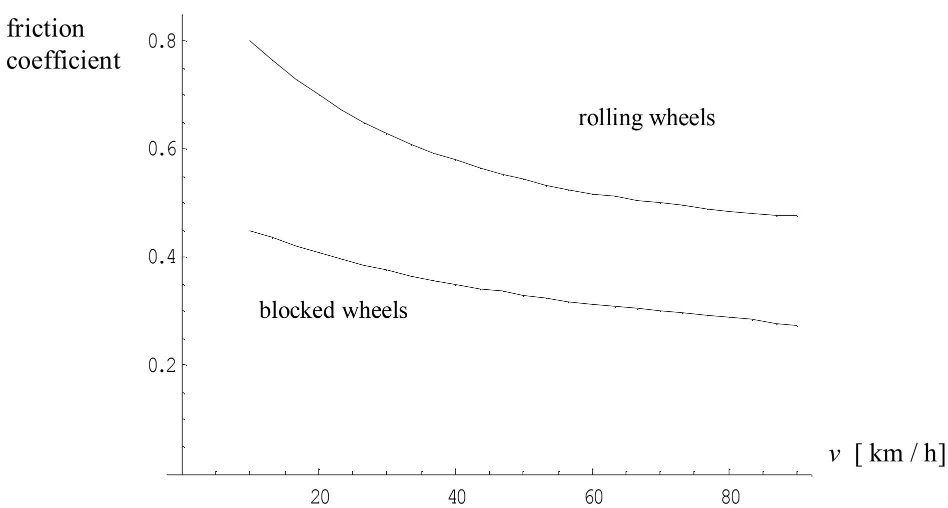
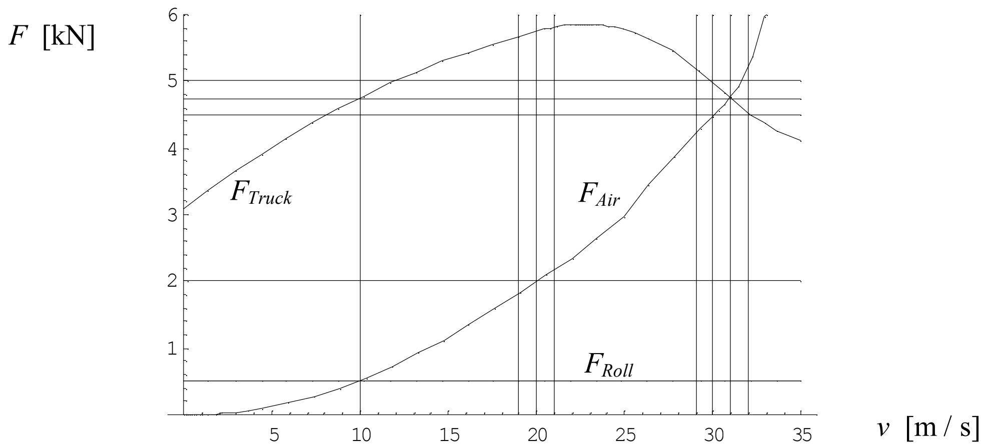


Figure 38: Roll friction, air friction and truck propulsion force

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9. Momentum

Definition

The definition of *momentum* is $M = F\,x$, with x the distance at which the force is exerted. Momentum is measured in Joules, [J] = [N m].

Momentum and work

One may note that *momentum* and *work* have the 'same formula' and the same unit of measurement. See Table 19. Are they the same ?

Table 19: Momentum and work compared

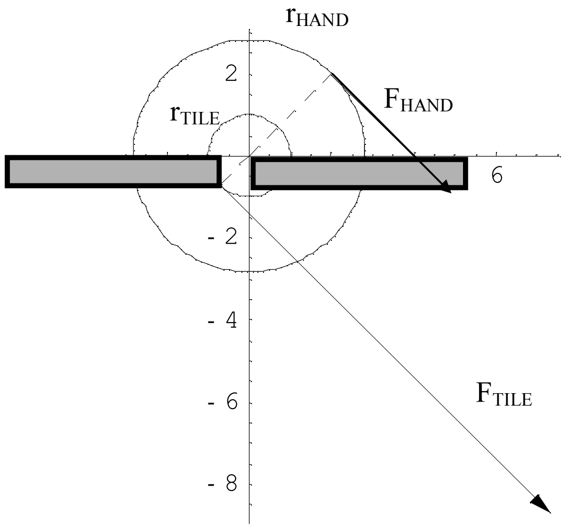
Concept	*Formula*	*Unit of measurement*
momentum	$M = F\,x$	[J] = [N m]
work	$W = F\,x$	[J] = [N m]

The answer to that question is "No". The crucial difference is that in **work**, the force is exerted *over* that distance, while in **momentum** the force takes place *at* that distance.

An example is the use of levers or crowbars to increase forces. Figure 39 contains a diagram of how a tile can be lifted using a crowbar. The crowbar reaches to the lower side of a tile, while resting on another tile. The long section of the bar makes a radius r_{HAND} and the short section makes a radius r_{TILE}. The force exerted by the hand is F_{HAND}, and the tile remains in rest only for some maximal value F_{TILE}. By experiments, like lifting the tile up directly, one can check that $F_{TILE} \gg F_{HAND}$, or that the crowbar amplifies F_{HAND}.

The question is how this amplification exactly works. By the mentioned experiments we find that $r_{TILE}\, F_{TILE} = r_{HAND}\, F_{HAND}$. Thus $F_{TILE} = (r_{HAND} / r_{TILE})\, F_{HAND}$, and the amplification is explained by the fact that $r_{TILE} \ll r_{HAND}$.

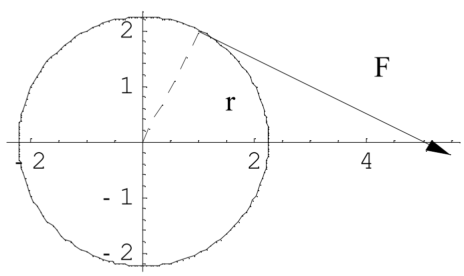
Figure 39: The effect of a crowbar

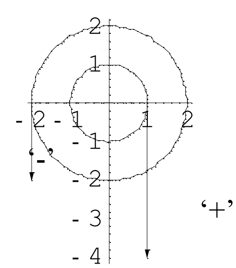


The combination of 'r * F' appears to play an important role here. Because of its role, we give it a separate name, and this will be "momentum". So the "momentum" of a force in relation to a (possible) center is the force times the distance to that center, $M = d\,F$.

Figure 40 (left) contains an example of that definition, and it may be noted that the distance is measured at a right angle to the force. Figure 40 (right) shows that a clockwise momentum is '+' and a counter-clockwise momentum '-'. So a force of 4 N at {0, 1} is at equilibrium with a force of 2 N at {-2, 0}. Note that for the equilibrium only the size of the force and its distance to the point of reference is required, and its + or - direction, but not the angle with the horizontal plane.

Figure 40: Momentum = distance × force





Equilibrium condition

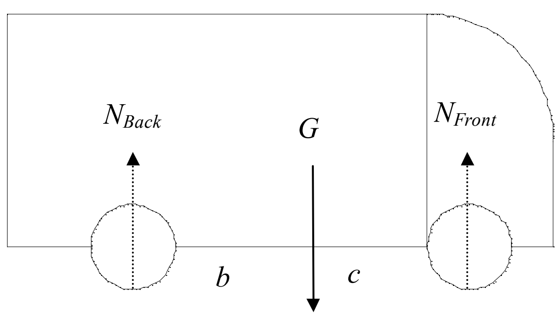
Above we regarded only two forces on the center. Of course there can be many more. Experiments show that the sum of all momenta should be zero if the center is to be in equilibrium. Hence we can reformulate the conditions of equilibrium for a solid body:

$$\Sigma F_x = 0, \quad \Sigma F_y = 0, \quad \Sigma M_p = 0$$

Forces on truck axles

A practical example of the use of momentum (apart from the crowbar) is the determination of the forces on the axles of a truck. For this, regard Figure 41. The center of gravity exerts a force G, and the tyres generate normal forces N_{Back} and N_{Front}.

Figure 41: Center of gravity for a truck

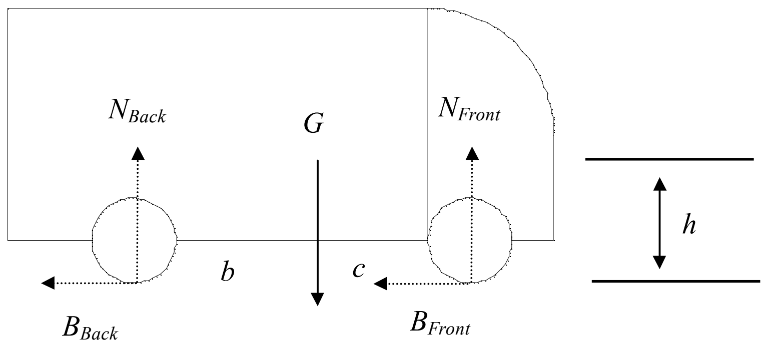


Since the truck is at rest in the vertical direction, we find that $N_{Back} + N_{Front} - G = 0$. This is only one equation. We need another equation to be able to solve for the forces. This we find in the momentum. If we take a point along the G power line, then the normal forces are at orthogonal distances b and c, and the equation for the momenta is: $b\ N_{Back} - c\ N_{Front} = 0$. (Thus, since G falls out, N_{Back} creates a clockwise and N_{Front} a counterclockwise movement). Now, having two equations and two unknowns, then: $N_{Back} = c\ /\ (b+c)\ G$, and $N_{Front} = b\ /\ (b+c)\ G$.

Forces on a braking truck

We can extend above analysis for a braking truck. Let the tyres exert braking forces B_{Back} and B_{Front}, with a resulting acceleration of $-a$, and let the center of gravity be a height h from the road. See Figure 42.

Figure 42: A braking truck



Taking the point of reference at the center of gravity gives the following equations:

(1) horizontally $\Sigma F_x = 0$ $\quad -B_{Back} - B_{Front} = m\,(-a)$

(2) vertically $\Sigma F_y = 0$ $\quad N_{Back} + N_{Front} - G = 0$

(3) in momentum $\Sigma M_p = 0$ $\quad h\,B_{Back} + h\,B_{Front} + b\,N_{Back} - c\,N_{Front} = 0$

Solving this gives the following result:

(4) Substitute (1) in (3): $\quad h\,m\,a + b\,N_{Back} - c\,N_{Front} = 0$

(5) Multiply (2) by b: $\quad b\,N_{Back} + b\,N_{Front} - b\,G = 0$

(6) Subtract (5) from (4): $\quad h\,m\,a - (c+b)\,N_{Front} + b\,G = 0$

(7) Solve for front seat: $$N_{Front} = \frac{b}{b+c}G + \frac{h}{b+c}ma$$

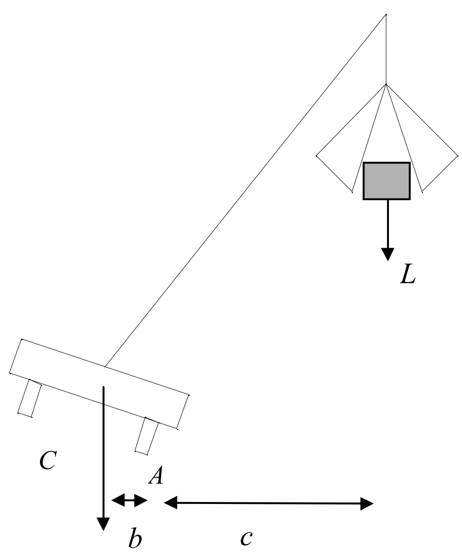
The first part of (7) we already encountered the situation when the truck was in stationary position. The second part is new for the braking situation. Braking apparently causes an additional downward force. Duck !

This deduction also clarifies that transported goods in the hold are subjected to more forces than may be apparant at first. In addition, with all these forces exerted on the axles, trucks may not be able to brake as fast as personal cars, which reduces road capacity.

When does a crane topple ?

Regard a crane with own weight C and a total grab-load weight of L, and regard the possibility that the crane topples over at pivot A. The distance between the center of gravity of C of the crane itself and A will be b, and the distance between the center of gravity of L and A will be c.

Figure 43: A toppling crane



The way to solve this kind of problem is to imagine a great circle, and to regard the momenta involved. The momenta are in equilibrium (and the crane is in danger of toppling) if $C\ b = L\ c$. Let us add a safety factor f, for example $f = 1.15$, then $L = b\ /\ (f\ c)\ C$. (Hint: make a graph of $L(c)$, for e.g. $b = 1.5$ m and $C = 10$ t.)

Crane performance is defined in terms of load L and reach c. We can find a simple formula for their relation as $L = X / c$ for $X = b\, C / f$. Normally, the own weight of the crane C, the pivot distance b, and the industry safety standard f are given, making X a constant. Crane manufacturers indeed supply hyperbolic displays of $L = X / c$.

Note that the following factors affect the risk of toppling:

- the pressure at point A, and the ability to withstand that pressure
- dislocation of the center of gravity of C, thus the change of b
- distortion in the crane itself, the ability to maintain c
- wind
- dangling load

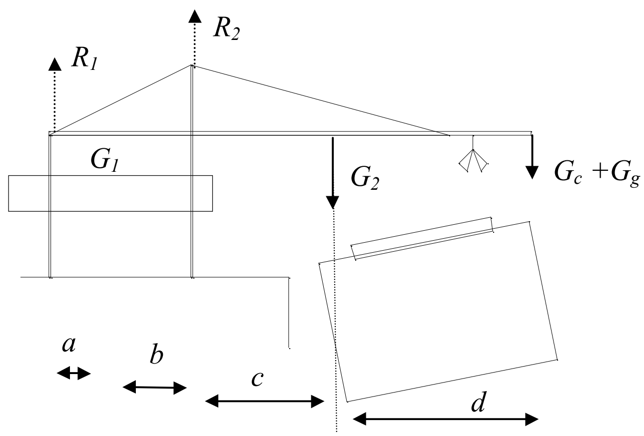
Gantry crane forces

We can now say more about the forces that occur in a gantry crane at work. For simplicity we reduce the problem to two dimensions. Table 20 reviews the major data, including the unknown reaction forces along the two gantry poles, and Figure 44 gives a graphical impression, also with the distances between the various force lines.

Table 20: Gantry crane data

Variable	*Symbol*	*Value*
left part of own weight	G_1	12,000 kN
right part of own weight	G_2	800 kN
weight of the cat	G_c	100 kN
total weight of loaded grab	G_g	500 kN
PM. weight of empty grab	G_e	200 kN
reaction force along first pole	R_1	?
reaction force along second pole	R_2	?

Figure 44: A gantry crane at work



We shall use the following distances: *a* for the distance between the first pole and the center of gravity of the left part of the crane; *b* for the distance from that center to the second pole; *c* for the distance of that second pole to the center of gravity of the right part of the crane; and finally *d* for the distance of that second center to the final end of the grab. We assume that the weight of the cat and the loaded grab is centered at the end of the cat. Numerical values are: $a = 6$, $b = 14$, $c = 16$ and $d = 32$ meters. The ship drawn has a width of 30 meters and a depth of 20 meters.

Since there is equilibrium of the vertical forces, $\Sigma F_y = 0$, we find:

$$G_1 + G_2 + G_c + G_g - R_1 - R_2 = 0$$

Since the crane doesn't turn, there is equilibrium in momentum too, $\Sigma M_p = 0$. Let us select the point where the second pole meets the quay as the pivot. Then we find that all forces are clockwise except for G_1 that is counterclockwise, so that:

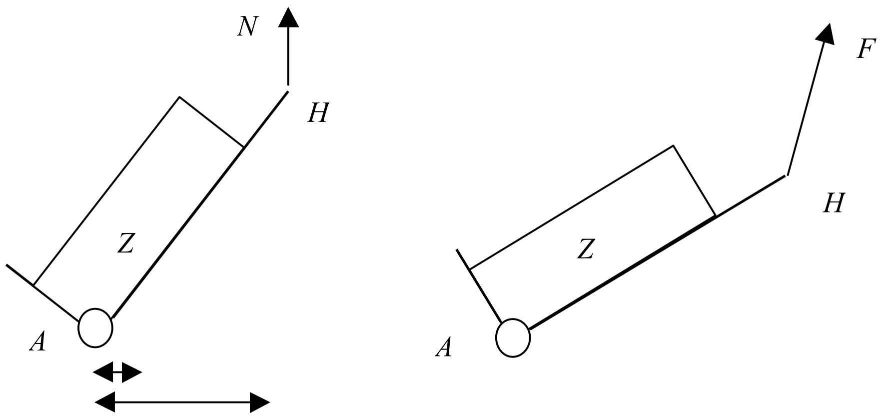
$$-b\, G_1 + c\, G_2 + (c + d)(G_c + G_g) + (a+b)\, R_1 = 0$$

Solving these two equations for the given numerical values gives $R_1 = 6320$ kN and $R_2 = 7080$ kN.

Question 1: Weight handling

A weight of 100 kg is transported by a hand trolley. We consider two positions: (1a) the trolley is in rest, (1b) the trolley is rolling, see Figure 45. In both cases the center of the wheel is *A*, the center of gravity is *Z*, and a force is applied at the handle *H* to hold the trolley. We neglect the weight of the trolley itself. Use *g* = 9.8.

Figure 45: Trolley (1a) stands, (1b) moves

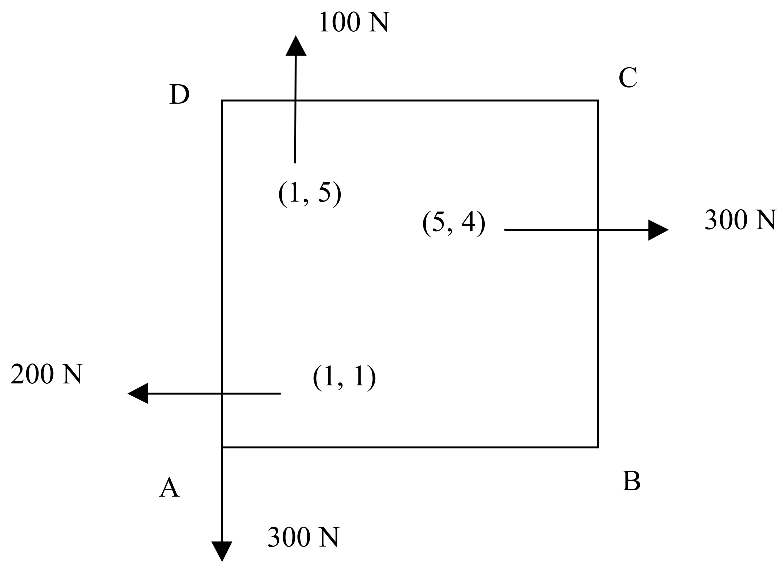


(a) The trolley has a current rest position in which the horizontal distances *AZ* and *AH* are 10 cm and 40 cm respectively. Calculate *N*.
(b) How would you manipulate the trolley, and adjust *AZ* and *AH* while the trolley still is in rest, such that the force applied at *H* would be minimal ? And what would be this minimal value ? (Note: the underside should not touch the floor, since tilting the trolley would cost energy again.)
(c) Now we regard the trolley when rolling. Its speed is constant, so the force *F* is only used to keep the trolley up and to overcome the roll resistance *R*. AZ = 60 cm and AH = 140 cm now. The force *F* makes an angle of 75° with the horizontal plane. Calculate *F* and *R*.
(d) Working safety conditions state that an employee is only allowed a maximal force comparable with lifting 25 kg. How many people are required to do this transport ?

Question 2: Square

In a square of solid metal ABCD, four forces apply at straight angles. See Figure 46, and note that the co-ordinates are taken with respect to point A at (0, 0). Determine the resultant force, the resultant force line and the co-ordinates where that resultant force applies.

Figure 46: Addition of forces and momenta



Question 3: Trolleys

Using momentum, we can better understand the properties of trolleys. Figure 47 shows a fixed and a moving trolley.

Suppose the trolley wheels have a radius of *r*. In the fixed trolley the gravity of the object to be lifted *L* and the lifting force *F* create opposite momenta for the center of the trolley wheel. For the moving trolley, the pivot can best be selected at point *O* in the diagram.

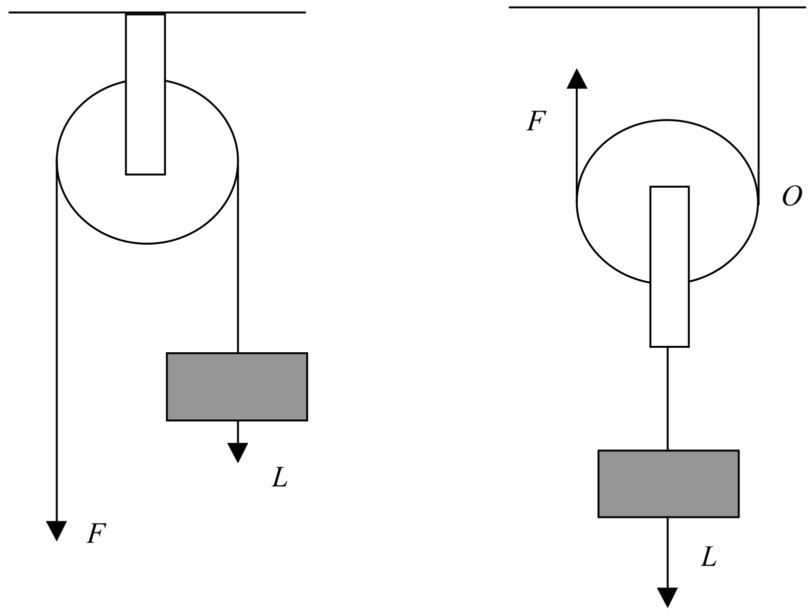
(3a) For the fixed trolley we can find that F = L.

(3a1) Now, find the appropriate relationship for the moving trolley.

(3a2) When the load is lifted for 10 meters:

(i) explain how much energy has been used for both systems
(ii) explain how much rope has been used for both systems (passed through lifting hands)
(iii) give the (dis-) advantages of the fixed trolley compared to the moving trolley.

Figure 47: Fixed trolley (left) and moving trolley (right)



(3b) Let there be two window cleaners of a weight of 90 kg. One window cleaner and his cabine of 25 kg have to be lifted. They use a fixed trolley.

(3b1) First, the one window cleaner, who is an amateur weight lifter and who can lift weights up to 125 kg, wants to lift his colleague, by pulling at the left side of the trolley (the force F). Can you determine whether he will succeed in doing so - if so, why, and if not, why not ?

(3b2) Later on, the weight lifter has gone, and the remaining window cleaner has to lift himself. He lifts himself to a height of 3 m.

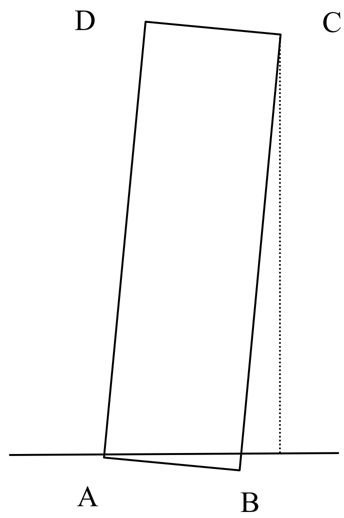
(i) Give the force that he has to apply.
(ii) Give the work that he has to perform.

Question 4: Tower of Pisa

The Tower of Pisa (built in 1174) has an angle of repose of 6%, see Figure 48. People wonder when it will topple.

a) The weight of the tower is about 15,000 tonnes. Does the weight matter ?
b) Assume that the tower is a rectangle ABCD, with sides 45 m and 13 m. Determine the center of gravity, and use the theory of momentum to explain whether there is a current danger of toppling or not.

Figure 48: Tower of Pisa



Question 5: Tom & Jerry

Your company owns two mobile cranes, called Tom and Jerry. The data about the cranes are in Table 21. Also, the cranes are only mobile in the sense that they can be transported to different places, but they cannot move while being used. In use they must be fixed on the spot. Also, they cannot turn around, just move up and down in one direction. Your company provides three kinds of services.

1) The first is to simply lift the object and move it over the distance that the crane can reach. This is a cheap service since it only involves a crane.
2) The second service is to lift the object onto a trailer, transport it by the trailer, and then lift it off the trailer again. This is most expensive, since this service requires fixing the crane twice while it also involves a trailer.
3) The third service applies to a short intermediate distance. It is called 'leapfrogging', and it consists of lifting the object over a short distance, move the crane, lift the object again, etcetera. Leapfrogging is expensive since the crane has to be moved and fixed each time, but is cheaper since it does not involve a trailer. Leapfrogging four times (setting up the crane five times) is cheaper than using a trailer, but more makes a trailer cheaper again.

Table 21: Crane data

	Tom	Jerry
Crane center weight	20 t	15 t
Distance crane center towards pivot	3 m	4 m
Mass of the grab itself	5 t	4 t
Safety factor f	120 %	120 %
Cost per hour	$500	$600

Now a client wants to lift a single heavy machine of 10 tonnes over a horizontal distance of 5 meters.

(a) Is this going to be a cheap lift, leapfrogging (if so, how many times), or will it involve the trailer ?

(b) What crane will be cheapest to use ?

10. Angular Motion

Introduction

Currently, we will study the relationship between translation and rotation. Our interest in this relationship has some obvious reasons:

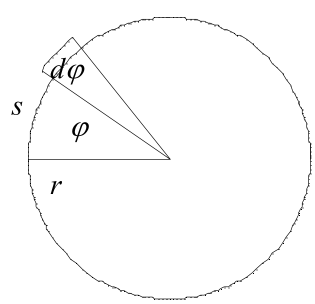
- transport often relies on the use of wheels
- combustion engines change translation (expansion of the combustion chamber) into a rotation (turning of the wheels)
- when lifting an object, we use pulleys.

Changing a translation into a rotation, and a rotation into a translation, will cause some friction, and loss of useful energy. We will want to minimise this loss. Our study of the relationship will clarify how this loss can be calculated, and it will help us to understand why the loss cannot be avoided in many cases.

Basic concepts

Figure 49 displays the main variables in our discussion. In a circle with radius *r,* we defined the angle φ (in radians) as $\varphi = s/r$ for the associated arc *s*. Hence $s = r \cdot \varphi$. For example, the circumference of the circle is given as $2\pi r$, since the angle made by a full circle is $\varphi = 2\pi$. This chapter looks into the consequences when the angle is slightly changed, so that we get $d\varphi$.

Figure 49: Rotation



From dφ we can define 'angular speed' and 'angular acceleration'. Table 22 defines these notions for translation and rotation, and Table 23 gives the relationships between these notions.

Note that a 'rad' is a dimensionless number, since it means [m/m]. A useful insight is to see the arc as a part of a *cycle*, with **1 cycle = 2π rad**. This gives us a better grip on angular velocity as the number of cycles per second. When $\omega = x$ [rad/s], then $\omega = x \;/ (2\pi)$ [cycle/s]. The quantity $n = x / (2\pi)$ will be called the *frequency*.

Table 22: Definition of distance, speed and acceleration, for translation and rotation

Translation	*Formula*	*Dimension*	*Rotation*	*Formula*	*Dimension*
Distance	s	m	Angle	φ	rad
Speed	$v = ds / dt$	m / s	Angular speed	$\omega = d\varphi / dt$	rad / s
Acceleration	$a = dv / dt$	m / s^2	Angular acceleration	$\alpha = d\omega / dt$	rad / s^2

Note in this table that we use Greek symbols for rotation.

Table 23: Relationship for distance, speed and acceleration between translation and rotation

Distance	$s = r \,.\, \varphi$ (for example the circumference $O = 2\ \pi\, r$)
Speed	$v = ds / dt = d\,(r \,.\, \varphi) / dt = r\, d\varphi / dt = r\, \omega$
Acceleration	$a = dv / dt = d\,(r \,.\, \omega) / dt = r\, d\omega / dt = r\, \alpha$

Earlier, we introduced the notions of *momentum, work* and *power.* It appears that these notions allow us to better understand the relationship between translation and rotation. First of all, a *momentum* means the exertion of a force *at* a distance, while *work* is the exertion of force *over* a distance. Let us now regard a force along an arc. Then the force *along* the arc also means a force *at* a distance *r* from the center of a circle. So we should find a certain relationship between work and momentum. This relationship is given in Table 24.

Table 24: Relationship between work and momentum, and power and momentum (in terms of translation and rotation)

	Translation	*Rotation*	*Dimension*
Force *F*	$F = m \, . \, a$	$F = m \; \alpha \; r = M / r$ ([21])	N (Newton)
Work *W*	$W = F \, . \, s$	$W = F. \, s =$ $= F \, r \, s / r = M \, . \, \varphi$	J (Joule)
Power *P* **(Energy flow)**	$P = W / t =$ $= F \, . \, s / t = F \, . \, v$	$P = W / t =$ $= M \, . \, \varphi / t = M \, . \, \omega$	W (Watt)

Note in this table that we express translation by *F* and rotation by *M*.

Centripetal force

When a mass has a circular orbit, it also has the tendency to leave the orbit and to fly out straight (inertia), and hence a force has to be applied to keep it in its orbit.

The centrifugal force is the force driving away from the center, and the centripetal force is the force directed to the center. In equilibrium these forces are equal.

The formula for the centripetal acceleration is: $a_c = v^2 / r$.

An application is the following. Suppose that you work at an airport and that today it is busy and planes have to wait till they can land. Suppose that a certain plane has 5 tonnes of fuel left, while normally it burns 10 tonnes of fuel per hour for steady level flights. You figure that it can stay in the air for half an hour, and ask the pilot to circle about for say 25 minutes. She starts to panic, and you better work on question 2 below.

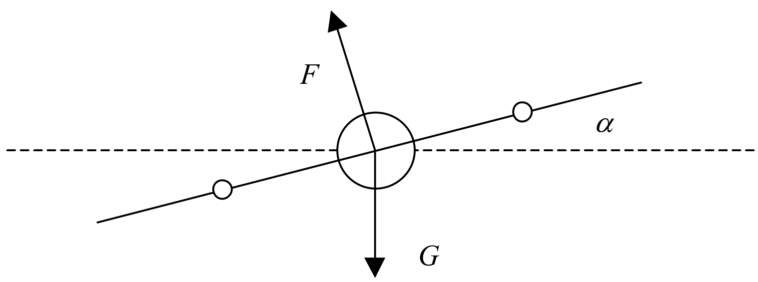
[21] Note that $F = m \, a$ & $M = r \, F$ give $M = r \, m \, a$. And with $a = \alpha \, r$, $M = m \; \alpha \; r^2$

Example questions

1) The Moon orbits the Earth in 27.3 days at a distance of 384,000 km. Give its orbital speed.

2) A Boeing 747-300 with 400 passengers and weighing 380 tonnes is on the way from Amsterdam to New York. Note that flying is possible since the air current under the wings generates a lift F at a right angle with those wings. Lift and gravity both apply at the center of gravity, as shown in Figure 50. Use $g = 9.8$.

Figure 50: Airplane making a turn



(a) The plane first flies in a steady level flight, horizontally and in a straight line (thus $\alpha = 0$). Calculate the lift for this cruising phase.

(b) Above England, the plane makes a curve with a radius of 25 km. To do this, the plane makes an angle with the horizon ($\alpha = 14°$). Since one wants to keep the plane at the same height, it appears necessary to increase the speed of the plane.

i) Explain why keeping the same height requires a higher speed.

ii) Calculate this speed.

11. Energy Transformations

The relationship from E_{in} to E_{out} is called the transformation. We can regard three useful transformations here:

1. transformation by a lever
2. transformation of translation into rotation
3. transformation of rotation into rotation

Energy transformation by a lever

Above, in the chapter on Momentum, we introduced the lever, and discussed it while using the example of lifting a tile using a crowbar. Regard Figure 39 again, and recall that

$$r_{\text{TILE}}\ F_{\text{TILE}} = r_{\text{HAND}}\ F_{\text{HAND}}$$

Let the hand move a distance s_{HAND}, so that the energy input is $E_{in} = F_{\text{HAND}} * s_{\text{HAND}}$.

Then the tile moves a distance s_{TILE}, so that the energy output is $E_{out} = F_{\text{TILE}} * s_{\text{TILE}}$.

If we make only a small movement, then geometry tells us that the ratio of the *s*'s is equal to the ratio of the *r*'s. Thus $s_{\text{HAND}} : r_{\text{HAND}} = s_{\text{TILE}} : r_{\text{TILE}}$.

Then we find:

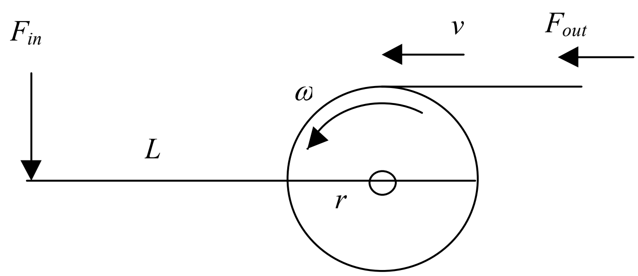
$$E_{in} = F_{\text{HAND}}\, s_{\text{HAND}} = F_{\text{HAND}}\left(r_{\text{HAND}} \frac{s_{\text{TILE}}}{r_{\text{TILE}}} \right) = \left(F_{\text{TILE}}\ r_{\text{TILE}} \right) \frac{s_{\text{TILE}}}{r_{\text{TILE}}} = F_{\text{TILE}}\ s_{\text{TILE}} = E_{out}$$

Thus in this simple theoretical case of a lever, we find an energy efficiency of 1. (In practice, of course, there will be friction at the rotation point, reducing the energy efficiency.)

The problem of a lever is that it cannot be used to maintain a flow of energy. The following kind of system however can be used.

We are all familiar with the water wheel in which the linear flow of the water is transformed into a circular movement. We are similarly familiar with bicycles, and we may now note that the basic model of the propulsion of a bicycle is that the pedals provide vertical power (a translation) and that the chain makes a round movement around the toothed wheel (rotation). Figure 51 provides the basic graph.

Figure 51: Translation into rotation



Note that L is the distance of F_{in} to the center, and thus includes r. The basic relationships then are $F_{in}\, L = F_{out}\, r$ and $v = \omega\, r$.

We then find:

$$P_{in} = M\ \omega\ = F_{in}\, L\ \omega$$
$$P_{out} = F_{out}\, v$$

And again $P_{in} = P_{out}$ and $\eta = 1$.

An efficiency of 1 is not realistic, since energy will be lost to friction. If we want $P_{out} = \eta\ P_{in}$ for $\eta < 1$, then we have to revise the relation of momentum to:

$$\eta\ F_{in}\, L = F_{out}\, r$$

Note that $L\,/\,r$ is called the basic reduction, and is often denoted by i_0. (NB: $i_0 \geq 1$.) Hence:

$$F_{out} = \eta \ i_0 \ F_{in}$$

In other words, the output force is determined by the input force, the basic reduction, and the efficiency of the process.

Energy transformation of rotation into rotation

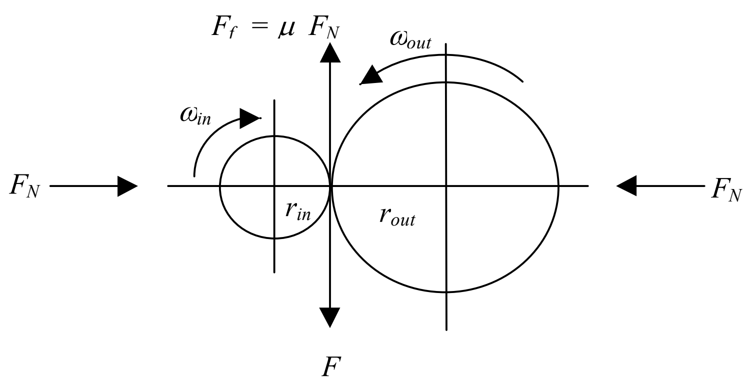
A clear example of the transformation of a rotation into another rotation are gears.

Human muscles characteristically work best at a rather low but steady rate. They can operate at peak performance, but then get tired quickly. Riding a bicycle on a slope may force the muscles to operate at that peak performance. However, using gears, the effort of the muscles can be reduced to their optimal level, and though the trip may last longer, the person may get less tired.

Thus with $P = F\ v$, an optimal level of P and an increase in F imply a reduced v. The impact of the use of gears is that the power at the pedals remains the same while the output speed of the wheels is adjustable.

Let us regard the example when the transmission is done by using friction only. Thus we do not use toothed wheels, but two normal wheels that are pressed together with a force F_N that causes a friction $F_f = \mu \ F_N$. The situation is depicted in Figure 52.

Figure 52: Transmission by using friction only



Properly accounting for the forces, we find that the input wheel exerts a force F on the output wheel, and meets a reacting friction $F_f = \mu\ F_N$. Thus $F = F_f = \mu\ F_N$.

We also find:

$$M_{in} = F\ r_{in} \quad \text{and} \quad P_{in} = M_{in}\ \omega_{in}$$

$$M_{out} = F_f\ r_{out} \quad \text{and} \quad P_{out} = M_{out}\ \omega_{out}$$

The ratio $i = \omega_{in} / \omega_{out}$ will be called the 'transmission ratio'. Now clearly, if $P_{out} = \eta\ P_{in}$ then:

$$M_{out} = P_{out} / \omega_{out} = \eta\ P_{in} / \omega_{out} = \eta\ M_{in}\ \omega_{in} / \omega_{out} = \eta\ i\ M_{in}$$

or the output momentum equals the input momentum adjusted for the transmission ratio and the efficiency of the process.

While this deduction has been done for flat wheels using friction, a similar deduction holds for toothed wheels. A practical observation is that for toothed wheels about 1% of the energy is lost at a transmission step. And for n steps: $\eta = \eta_1\ \eta_2\ \ldots\ \eta_n$.

Example questions

1) A gear box has 5 toothed wheels, and each transmission step loses 0.99% of the energy. What is the total energy efficiency η?
2) The speedometer of a car shows 120 km per hour while the motor revolution counter shows 3000 cycles per minute. The radius of the tyres is 0.25 m. Give the total transmission ratio i.


NELCON

12. Forces and Stresses in Materials

Introduction

With the increase of transport flows around the world, there is a great economic pressure upon transport and transshipment companies to increase the scale of operations. Vehicles such as ships become larger and larger, and with them cranes and other equipment grow in size and speed too. To better understand the possibilities for growth, we now look into the issue that with the increase in size, that there can be a point where the forces become too big, and that our machines break down. In designing equipment, we have to reckon with the forces and the tensions involved, and the possible distortions of the building materials.

For example, regard a container gantry crane. Current maximum ship width in Rotterdam harbour is about 18 containers, which, at 2.44 m width per container, is about 55 m. The distance from the ship to the supporting pole of the crane can be as much as 10 m. Thus, the trolley that lifts the containers may have to run a distance of 65 m on a beam that is only supported by a pole on one side. With a container of 25 tonnes, the spreader of 12 tonnes, the trolley of 20 tonnes, and the beam weight itself of 90 tonnes, there is a weight of about 150 tonnes to be supported. If we use two poles, this is about 75 tonnes per pole. Currently, there are new plans to increase ship with to 22 containers. Given that tensions are large already, can we deal with the tensions caused by the size of this new proposal ? Note that we require the supporting beam for the trolley to remain as flat as possible, without bending that would make it more difficult to lift the containers.

One should note the following problem: A larger construction increases the weight of the construction, and this again requires a larger construction. So there is a weight multiplier.

To start with, we should be clear about some terminology:

- We see a basic process that implies some force; this force is exerted on a construction; the construction is made of some material; and the construction has a certain shape.
- When the force is very large, there can be a distortion of the piece of equipment. There is a distortion when the shape of the equipment changes. Distortion generally impairs the functioning of the equipment. The distortion is destructive when the equipment no longer functions properly as a result of that change of shape. Thus: ‘shape’ enters as an important physical concept.
- When the force is removed again, the piece of equipment may bounce back to its original shape: in that case the equipment is said to be elastic. However, if

the equipment remains in its distorted form, the equipment is said to be inelastic.

- The properties of pieces of equipment can be reduced to the properties of the building materials and the properties of fixtures.

A clear example is when a crane tries to lift too heavy an object. The lifting cable may snap, or the crane itself may bend and finally break down. A less obvious example is when a crane is working properly at its maximum weight, but then there is a sudden windflash that pushes the force over its maximum. A even less obvious example of the relevance of the study of tensions is that tensions can be used to actually strengthen pieces of equipment. The use of concrete under tension is an example of this. Or, a steel plate can be pressed into a specific shape that appears to be stronger than the plate by itself.

Here we only regard the tension that results from *pulling* at objects (stress) as opposed to pushing (pressure).

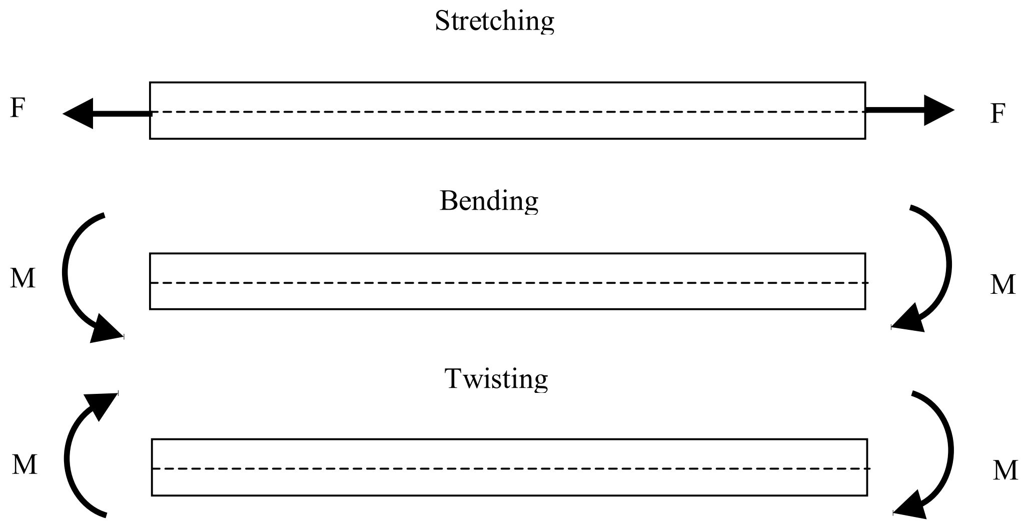
Basic assumptions

To understand these issues we will regard a simplified situation:

- **prismatic** beams, that is, for each section that we might take, the center lies on the same straight line
- the length of the beam is much larger than the diameter
- **homogeneous** materials, that is, for each material sample that we might take, it has the same composition
- **isotropic**, that is, it has the same properties in all directions
- the forces are exerted at the extremities of the beam (while we do not investigate how this is actually done)
- we limit our attention to **stretching** and **bending**.

Figure 53 displays what we mean by stretching, bending and twisting. What is important for stretching is that the forces are perfectly aligned. If the force lines of the forces at the extremities and the center of the bar are perfectly aligned, then the bar remains straight, and doesn't bend or twist.

Figure 53: Stretching, bending and twisting



Definition of stress and Hooke's law

Let us take a prismatic steel bar with a force F on it, and let us make a section. The surface of that section is A, for a round bar with diameter d and radius r, we clearly have $A = \pi r^2 = \pi d^2 / 4$. We already encountered the 'force per square meter' for the *pressure.* Now we are concerned with *stress* (pulling), and it appears that the common unit is the millimeter, so we define the stress as $\sigma = F / A$ and express this in N / mm^2. The relation $\sigma = F / A$ gives the relation between external force and internal stress.

For example: a force of 10 kN applied to a steel bar with a diameter of 10 mm creates a stress of $\sigma = F / A = 10$ kN / (π 100 / 4) = 400 / π = 127.3 N / mm^2. The relevant question for this example is whether this tension is large or small. Normally, we would ask a materials expert for his or her opinion.

In the year 1660 Robert Hooke did experiments on stress, and he found his 'law on elasticities'. This law is as crucial to engineers as Newton's law. Hooke's law states that the stretch of a material is proportional to the length of the material and the force applied to it, and inversely proportional to the thickness of the material.

With L the length of the material when there is no force, and dL the stretch, Hooke found that stretch shows this proportionality: $dL \approx F\,L / A$.

The coefficient of proportionality is expressed with the symbol E, giving $dL = F\,L\,/\,(A\,E)$.

Each material has its own coefficient of proportionality. For steel $E = 2.1\ 10^5$ N / mm^2, for aluminium $E = 0.7\ 10^5$ N / mm^2.

We shall use the symbol ε for the relative stretch $dL\,/\,L$. For example a stretch of 0.5% would give the results $\varepsilon = dL\,/\,L = 0.005$. Also, we used the symbol σ above to denote the stress $F\,/\,A$. Then Hooke's law can be written as:

$$dL = F\,L\,/\,(A\,E)$$

$$\varepsilon = dL\,/\,L = F\,/\,(A\ \ E) = \sigma\,/\,E$$

$$\sigma = E\ \varepsilon$$

Thus a 0.1% stretch of a steel bar (with $E = 2.1\ 10^5$ N / mm^2) would generate a stress of 210 N / mm^2.

Hooke's law captures different aspects of engineering. The force F is determined by the *process* that is being engineered, for example by the tonnes that have to be lifted. The ratio $A\,/\,L$ gives the average surface per meter and is determined by the *shape* of the object. The value of E is determined by the *kind of material* used. The ratio $E\,A\,/\,L$ is called the stiffness or rigidity of a bar, and it equals $F\,/\,dL$ or the force per stretch. Note that when L is given (a crane must cover a certain distance) and when also the kind of material is given, then the rigidity can only be influenced by the diameter of the bar.

Elasticity and its range

Extensive experimentation has shown that Hooke's law on the relationship between tension and stretch is valid only for a limited range. In fact, bar stretching has shown that steel bars have basically four phases:

1. the range of elasticity for which Hooke's law is valid: when the force is released, the bar returns to its original length
2. the range of inelasticity for which Hooke's law isn't valid:
    a. The *yield point*: the length of the bar can be increased without a rise in tension. Sometimes the material is said to 'flow'. Also, the bar distorts, meaning that when the tension is released, then the bar does not return to its original size: some of the increase in length is permanent.
    The yield stress is denoted as σ_{Yield}.
    b. then a flexible range: to stretch the bar, it again requires additional tension; but part of this increase is also permanent
    c. and then it breaks. The stress at which this occurs is called σ_{B}.

The above particularly holds for so-called 'structural steel' or 'mild steel' or 'low carbon steel'. This is used extensively in buildings, bridges, cranes and other machinery.

Steel can be made stronger by adding certain components like nickel, vanadium, chromium. These 'strong' steels don't flow. For these kinds of steel researchers make frequent use of the
$\sigma_{0.2}$ point, which is the point with a maximum of 0.2 % of permanent deformation.

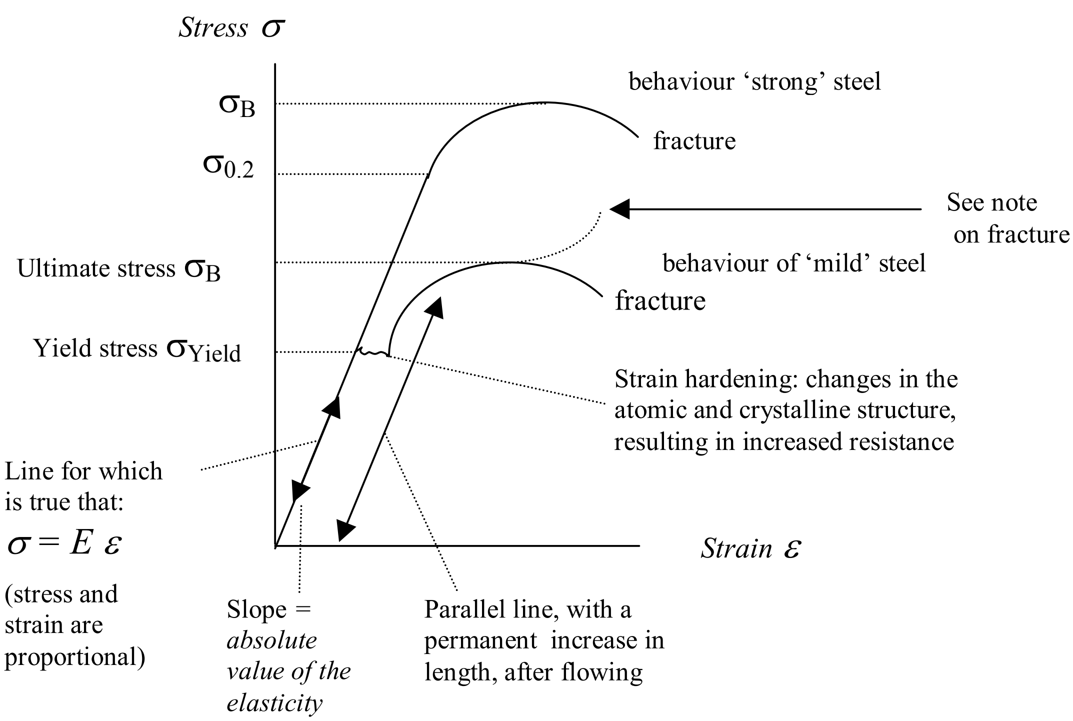
When building steel constructions, we will use σ_{Yield} and $\sigma_{0.2}$ as limiting values.

Figure 54 gives a graphical display of these phases in stretching, and also explains the difference in behaviour by 'mild' and 'strong' steels.

Hooke's law is given as a straight line through the origin, with *E* given by the slope of the line.

Note that in the inelastic range, when the tension is reduced, the stretch reduces along a line *parallel* to the original line.

Figure 54: Stylized stress & strain diagram of steel



Note on fracture: It appears difficult to accurately measure the stress when the bar is breaking. At breaking, the bar namely pinches in, which causes the recording instrument to register a reduction of stress, while actually, since *A* is reduced, the stress should be increasing. So Figure 54 basically plots recorded stress, while the dashed line above σ_B gives the theoretical stress.

Decision aspects

When constructing a piece of equipment, and choosing building materials for it, we have to consider the constructive, technological and economic conditions.

The economic condition is that we want a fair price for a good product. The technological conditions are related to the way that raw materials are processed into the final building materials, for example the mixing of metals into steel alloys. The constructive conditions are relevant for the technical application of these materials.

The most important constructive condition is the maximal tension for the material. This is the limiting value that is allowed for the process under consideration.

The maximal tension is not a fixed constant, but depends upon the kind of application, the kind of surface, the temperature, the situation and the safety factors that one chooses. It thus is very important to be informed about working conditions and about the tension that the building material can withstand without breaking down.

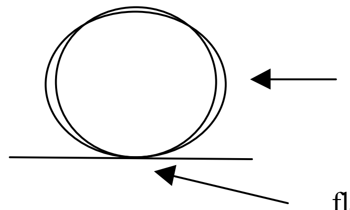
Another condition is the life span of the equipment. Even though a piece of equipment may have been designed such that the maximal tension never occurs, there still are other factors that limit its life span. Relevant processes are corrosion, erosion, fatigue, creep and combinations of these.

Given the importance of having good equipment at a reasonable price, this discussion may clarify the need for the research that is done in material science.

Tension and roll resistance

We now may also better understand one aspect of roll resistance. A rubber tyre or steel wheel is flattened at the place of contact with the surface below, and stretched elsewhere. Figure 55 gives an exaggerated view. When rolling, the wheel is continuously reshaped, while the forces remain in the elastic range. However, each reshapement is a displacement of material, or a *dx*, and *F* * *dx* gives *work*. This energy is essentially lost in the heating up of the wheel.

Figure 55: Material tensions in a rolling wheel



Example questions

Results of material science can be reported in tables like Table 25. The data in this table can be used to answer questions like the following.

Question 1: A steel bar of non-composite steel Fe 410 with $E = 2.1\ 10^5$ N / mm^2 is subjected to a tension. The bar has a length of 1 meter and a square section with sides of 1 centimeter.

a) Compute the force required to stretch this bar with 1 mm.

b) What is the stress in the bar at that moment ?

c) If the bar would be used in a crane, would that stress be admissible ?

Question 2: A steel beam of non-composite steel Fe 410 with $E = 2.1\ 10^5$ N / mm^2 and of circular diameter is used in a gantry crane. The force applied to the beam will be 75 kN. Determine the diameter of the beam.

Table 25: Material properties

Material	*Name*	*Fracture stress* *N / mm^2*	*Yield point* *N / mm^2*	*Maximal stress for cranes*
non-composite steel construction steel	Fe 410 Fe …..	420 - 50 ….	260 ….	175 ….
composite steel	2 C 25 …..	….	….	….

13. Some Old Exams

The exams below have been adapted from real exams. The reason for the adaptation is that the order of the chapters has been changed when rewriting this text. The current setup is that:

- Fall Semester exams cover chapters 1 - 7 (inclusive).
- Spring Semester exams cover chapters 8 - 12, while using 1 - 7.

The exams are targetted at a sit of 1¼ hour, though students are allowed to use 2 hours.

Note: The points allocated to the questions are indicative. They normally also depend upon the time spent on a subject in a given year.

Note: Depending upon the kind of class, students are allowed to use the book.

Fall Semester A

1) (10 points) Why is transshipment so important in transport ?
2) (10 points) What have been the most important developments in transshipment ? (Use a paragraph per kind of development, and give each paragraph a short heading.)
3) (25 points) Regard the free digging phase of a grab that unloads a ship. The material goes via a bunker onto a conveyer belt. Use the data in Table 26. Then:
    a) Give the number of crane cycles per hour.
    b) Plot the mass inflow in the bunker as a function of time for at least three cycles, using proper legends and mentioning the maximal value of the mass flow.
    c) Give the minimally required volume of the bunker.
    d) Plot (below or next to (b)) the mass outflow out of the bunker as a function of time for at least three cycles. Give the numerical value of the slope, and explain what its value stands for and why it is important.

4) (20 points) You are provided with the following data:

material	granular
transport angle	60°
transport speed	2 m/s
mass flow	800 t/h

You are invited to determine what type of conveyer belt type to use. What type do you propose ? Clarify your choice with a table containing some options, characteristics, and + and - scores.

5) (25 points) A ship with a load L = 80,000 tonnes of coal is unloaded within T = 50 hours, using two cranes. Denote the mean mass flow as $q = L/T$. The performance of the cranes is given in Table 27.

   a) Produce a graphical display of $(dm/dt) / q$ against T.

   b) Determine the efficiency of the unloading process.

   c) An ideal continuous alternative would unload at a the same average speed of a crane, at any moment. Give the capacities of the current discontinuous method and that continuous alternative.

   d) Determine the cycle period in seconds during the free digging phase, when a grab type is used with a maximum total weight of 40 tonnes and a payload deadweight ratio of 1.2.

6) (10 points) Management considers the replacement of an existing crane-grab combination by a continuous system that relies on a pipe belt elevator. Data are provided in Table 28. Give the required belt width with an accuracy of 50 mm, assuming $dVc/dt = dVd/dt$.

Table 26: Data for question 3

ship	load	L	70,000 t
	unloading time	T	70 h
material	granular ore, with density	ρ	2,500 kg / m^3
process	with efficiency	η	5/12
grab	mass full grab	m_{GF}	50 t
	mass empty grab	m_{GE}	20 t
bunker	loading time from the grab	Tb	3 s

Table 27: Data for question 5

time	mass unloaded	remarks
0 *T* - .40 *T*	.70 *L*	freedigging
.40 *T* - .75 *T*	.25 *L*	
.75 *T* - 1.00 *T*	.05 *L*	clean up

Table 28: Data for question 6

type	*item*	*symbol*	*value*
crane - grab system	mass of a full grab	mf	25 tonnes
	payload deadweight ratio	PL / DW	1.20
	cycle period	Td	40 s
	material density	ρ	900 kg / m^3
pipe elevator system	speed	v	8 m / s
	belt width	B	
	belt width overlap of 10%	δ	0.10 B

Fall Semester B

Question 1: Pallet (20 points)

Pallet loads are commonly strapped with ropes to make for more stability. The effect of a rope is not just constriction of movement, but perhaps the major effect is that it exerts a force F that increases friction. Figure 56 displays the situation, with α giving the angle where the boxes are just not moving with respect to each other. We regard only the situation of the top box with mass m. While $G = m\,g$, we assume that $F = m.g$ too. The questions for you are:

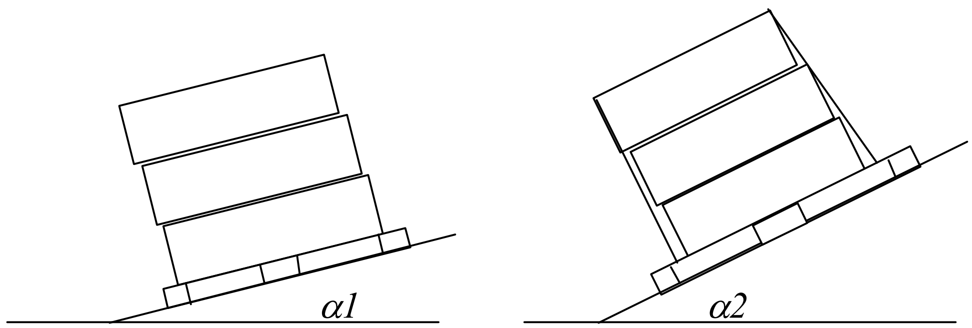
1. Give $\alpha 1$ for figure 1 without a rope around the boxes.
2. Give $\alpha 2$ for figure 1 with a rope around the boxes.

3. Determine the ratio $S = \alpha 1/\alpha 2$.
4. Give your conclusions about useful properties for boxes.

Note: use:

$$\frac{\sin(\alpha)}{1+\cos(\alpha)} = \tan(\frac{\alpha}{2})$$

Figure 56: Boxes without and with ropes



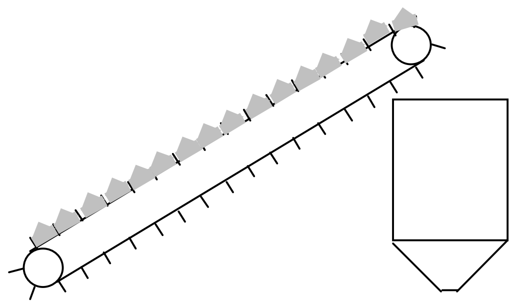
Question 2: Silo (20 points)

A 40 m high silo needs to be filled with grain, and one option is to use a conveyer belt at an angle. The grain has an angle of repose of $\alpha 0 = 25°$, and to prevent the grain from sliding down, the belt has been equipped with 10 cm high bars at 20 cm distance from each other, creating 'cells'. The bar height of 10 cm has been chosen so that the whole conveyer structure reaches its maximum supporting weight when the cells are just full. Figure 57 depicts the situation. To be precise: it has been an advertising artist who has given his impression, without thinking about the angle. Thus, the figure is just an 'artist's impression' and it may not be physically correct. The questions for you are:

1. Draw the correct situations for $\alpha = \alpha 0$ and $\alpha > \alpha 0$.
2. Decide which of the two cases has the higher carrying capacity and give the belt length.
3. Give your 'trained impression' of the situation when $0 < \alpha < \alpha 0$, assuming that the supporting strength of the structure is much larger.
4. State, in a few lines, whether this latter case is interesting for further R&D or not, considering trade-offs between structure costs, running speeds and carrying capacity.

In making your drawings, concentrate on just one or a few cells to convey the general situation. Use a drawing cell width of 4 cm and a height of 2 cm.

Figure 57: Loading a silo

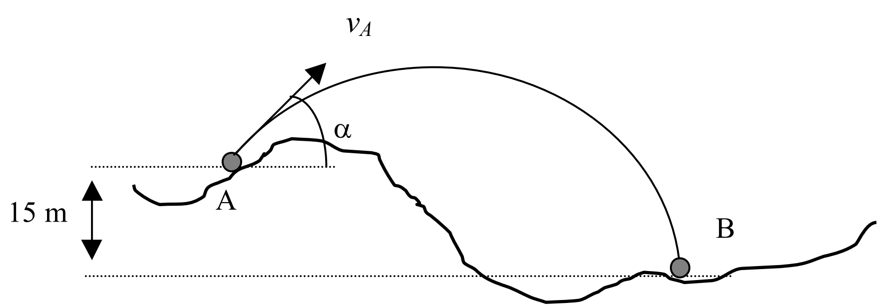


Question 3: Basic Physics (20 points)

A ball is thrown from a hill with a speed of 10 m / s and comes down 15 meters lower down the valley. The ball is thrown at an angle α. Air resistance is zero. With what speed will the ball hit the ground ?

Take g = 10 m / s^2. See Figure 58.

Figure 58: Ball thrown from a hill



Question 4: Factory Improvement (20 points)

You work at the costing department of a factory. The engineer presents himself and tells you that he has a suggestion for an improvement. There is a certain tool that is in use for 8 hours per day and that uses a constant electrical current of 100 kW from the city power supply. However, the engineer noted that the process served by the tool only uses 80 kW, and he didn't like the implied inefficiency. He claims that it is possible to increase efficiency by 4.2 % points if some changes are made

in the tool's use of power (and in the tool only). You like that, since your factory pays $0.09 per kWh. There is a catch though: the improvement will cost $1000. You are asked to compute the pay back period for this possible improvement.

Question 5: Cocoa Container (20 points)

More and more cocoa is going to be transported by container, witness the recent strikes and labour disputes in Amsterdam Harbour. Your company, a heavy user of cocoa, will get its dayly supply delivered by container. Of course, you might continue to ask for bags, but that will be costly. So your boss asks you to arrange for a company container crane. You draw up a list of requirements, see Table 29, and send out applications for tenders. Two suppliers react, Goodman & Son and Badguy & Partners. They both offer different cranes at different prices. The cranes appear to differ mainly in their power (in kW). Both suppliers have looked at your specifications, and advice you as to what you should need. See Table 30 where the prices are in thousands of dollars.

It appears that G&S is overall cheaper except for the most powerful crane. But G&S also advises you to buy in the lower price range, so you cannot accuse them of overpricing. Conversely, you might suspect them of advising in the range where they are competitive, and you might buy a crane that does not really fit your requirements.

B&P is overall more expensive, except for the most powerful crane. And they advise you to buy exactly this one.

Table 29: Specifications Company Container Crane

Item	*Value*	*Dimension*	*Item*	*Value*	*Dimension*
maximum load	40	t	av. acceleration	0.4	m/s^2
spreader	12	t	efficiency	0.8	none
average lift speed	0.7	m/s	(PM: gravity	9.81	m/s^2)

Table 30: Tenders

Prices per kW class	*360*	*372*	*448*	*466*	*Advice*
Goodman & Son	$100	$120	$150	$200	372 kW
Badguy & Partners	$110	$130	$160	$190	466 kW

There is a marked difference between the two advices. You might ask an independent engineering consultant to advise you on your choice. But that will cost you $1000 per day, while, actually, your boss hired you because he thought you were well versed in transport issues. Then: Determine the kW class that you need, and then decide what tender to accept. Provide adequate calculations to explain matters to your boss.

Spring Semester A

Question 1: Formula Review (15 points)

Answer the following questions by clearly defining symbols and stating their dimensions.

(a) What is the kinetic energy of an object with mass m [kg] and speed v [m/s] ?
(b) What is a momentum ?
(c) What is work ?
(d) What is the conceptual difference between momentum and work ?
(e) What is a common misunderstanding about the power of a machine ?

Question 2: Pollution (20 points)

It is assumed here that traffic pollution on a flat road is proportional to the propulsion force of the engine. Regard a passenger car with the following specifications:

mass	$m = 1000$ kg
roll friction coefficient	$f = 0.02$
frontal area	$A = 2\ m^2$
air density	$\rho = 1.25\ kg / m^3$
gravitational constant	$g = 10\ m / s^2$
air friction coeffficient	$c_w = 0.4$

Compute the percentage increase in pollution when the speed is increased from 100 to 120 km per hour.

Question 3: Pneumatic wheat discharge (20 points)

Nowadays, wheat bulk carriers are often discharged by pneumatic methods. High speed air currents lift up the small wheat grains and transport these through a tube to a conveyer belt for further transport. When regarding the air lift by itself, physics tells us that a wheat grain is subjected to two forces, namely gravity and the carrying force of the air current. For the latter we can take the formula that we have used for the air resistance encountered by cars. See Figure 59.

Figure 59: A wheat grain lifted straight up by air

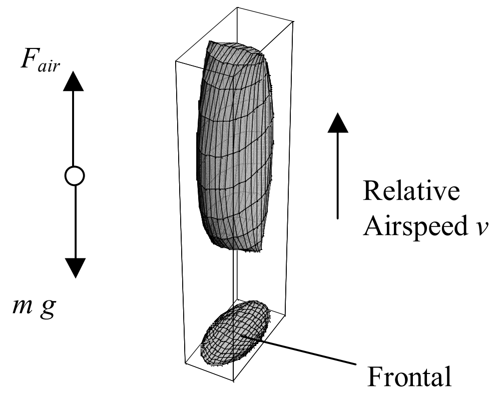
Wheat: m = $0.486\ 10^{-4}$ kg

c_w A = 10 mm^2

ρ_{wheat} = 600 kg / m^3

Air: ρ_{air} = 1.2 kg / m^3

Gravity: g = 10 m / s^2

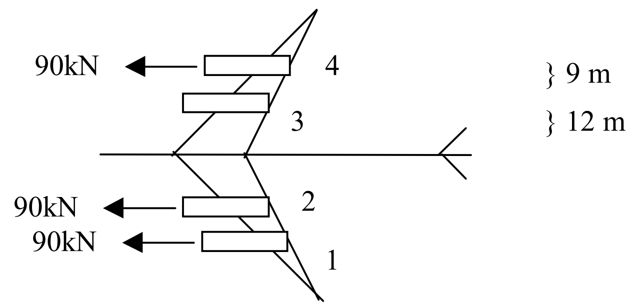


Use the data in Figure 59 to compute the minimally required (relative) air speed v.

Question 4: Plane (20 points)

A commercial airliner with four jet engines each producing F = 90 kN of forward thrust is in a steady, level cruise when engine number 3 suddenly fails. Determine and locate the resultant of the three remaining engine thrust vectors. Treat as a twodimensional problem. See Figure 60. NB. Suppose that all engines are in one line at a right angle with the center of the plane. Also, let the outward motors be at distance b = 21 m from the center and the inward motors at distance a = 12 m, so that the distance between the inward and outward engines on one side is 9 m.

Figure 60: Plane



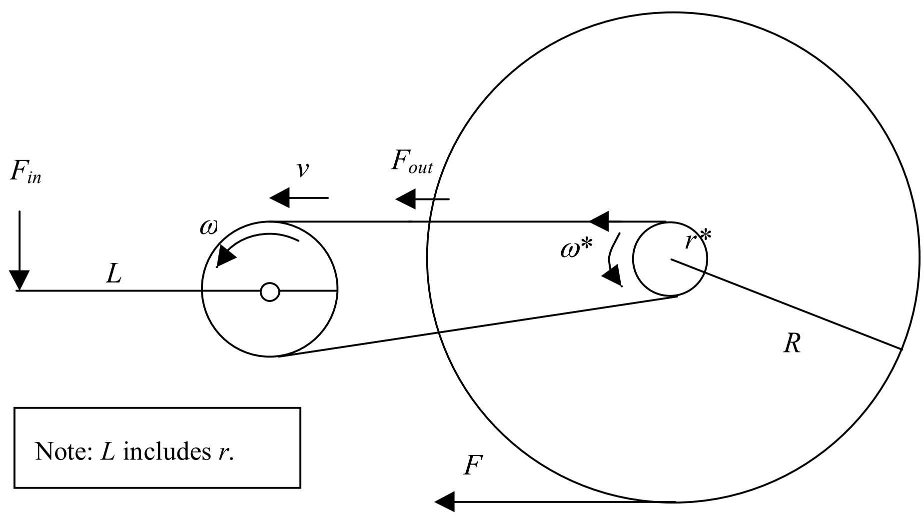
Question 5: Bike (25 points)

Figure 61 gives the main components of the propulsion system of a bicycle. Assuming that there is no friction:

(a) Give P_{in}, P_{out} and the formula for the efficiency η.

(b) Determine the propulsion force F as a function of the input force on the pedal F_{in}, using the momenta around the centers of the crank and the wheel.

Figure 61: Bike: pedal, crank, chain, axle and wheel



Question 1: Formula Review (20 points)

Answer the following questions by also clearly **defining** symbols and stating their **dimensions**.

(a) What is angular speed ?
(b) What is energy efficiency ?
(c) What is work ?
(d) What is the conceptual difference between momentum and work ?
(e) What is a common misunderstanding about the power of a machine ?

Question 2: Propellor (25 points)

Regard a propellor with a radius of 1.2 meter, a width of 7 cm and a thickness of 0.5 cm. The propellor has been made of steel with density of $\rho = 3000$ kg / m^3 and with $E = 2.1\ 10^5$ N / mm^2.

(a) How many cycles per second must the propellor make so that its tips have the speed of sound of 340 m / s ?
(b) Show for an arbitrary angular speed ω that the centripetal force is smallest at the center and largest at the tip.
(c) Use the laws $F = m\ a$ and $m = \rho\ V$ and $\varepsilon = F / (A\ E)$ to show that $\varepsilon = \rho\ L\ a / E$.
(d) Using a slice at the tip of $L = 1$ mm, calculate the strain and stress at the tip caused by (only) that force of cycling with that speed of sound.
(e) Is this computed value lower or higher than $\sigma_{0.2}$?

Question 3: (25 points)

A truck on a flat road with a mass of 30 tonnes drives at a speed of 81 km/h. We neglect other forces except for gravity and roll resistance. Its roll resistance has been given by the function:

$$F_{roll} = 0.45\ \ m\ g\ cos(\alpha)$$

where g = 10 m / s^2. The truck transports breakables that can only be subjected to an absolute acceleration (or deceleration) of 2 m / s^2.

(a) Determine the normal braking distance of the truck, if the goods were not breakables. Determine also the acceleration and the braking time involved.

(b) Determine the braking distance and braking time now that the goods are breakables.

Question 4: Insurance Rate (30 points)

You work at a warehouse where most of the storage places are constructed in steel. Annually, the engineer of your company together with an engineer of your insurance check the steel constructions. Today they report a problem at the A2 location. The insurance engineer remarks that he will advice an annual rate increase of \$1000, unless a non-composite steel bar of Fe 410 with $E = 2.1\ 10^5$ N / mm^2 is replaced by a composite steel bar of 2 C 27.5X with $E = 2.5\ 10^5$ N / mm^2.

The steel bar in question takes a central place in the storage rack of A2, has a length of 4 meters from ceiling to floor, and a round section with a diameter of 1.8 centimeters. The insurance engineer says that it may well carry a load of 5000 kg, and he does not see how employees working the storage area can avoid overloading the rack for one chance moment.

From earlier experience you know that it will cost \$3000 to replace steel bars in existing constructions, including the lost working hours from first emptying and then restocking the storage location. Doing what the insurance engineer says will come with a one-time cost of \$3000 but will save \$1000 annually in a higher insurance rate. However, you may also argue the insurance engineer's decision. Your company's engineer says that all is a matter of judgement here. The table that the insurance engineer uses is for cranes that work in dynamic and weather conditions, while these storage racks are inside and static. Before you can argue your case, you have to check how serious the situation is.

Table 31 contains more data. Use g = 10 m / s^2.

Table 31: Material properties

Material	*Name*	*Fracture stress* N / mm^2	*Yield point* N / mm^2	*Maximal stress for cranes*
non-composite steel construction steel	Fe 410 Fe …..	420 - 450 ….	260 ….	175 ….
composite steel	2 C 27.5X …..	500 - 520	320	250

(a) What is the stress in the bar at the insurance engineer's estimate ?

(b) What is the strain in the bar at the insurance engineer's estimate ?

(c) Is the situation so problematic, that permanent deformation has already occurred ?

(d) What is the weight load in the rack at the yield point ?

(e) Is the insurance engineer's estimated stress admissible according to the table's standards ?

(f) What is the maximum weight load in the rack according to that official standard ?

(g) Will the insurance engineer's advice solve the problem ?

14. Answers

1. Introduction

1) Cold storage requires insulation and thick walls. With the same width of 2.5 meters, it would become impossible to put two pallets next to each other. Other ways of stacking the goods would cause too much empty space, resulting in the phenomenon of 'transporting air'. Developing other pallets and stacking equipment would be very costly. So, efficient transport using the presently available handling equipment would require a truck width of 2.6 meters. Nevertheless, don't let yourself be tricked into questions with a political angle. Whether this dispensation should be allowed or not, depends upon your political views on balancing road safety and economic efficiency. It doesn't depend on physics.
2) An alternative is to use a mobile crane that can reach into the factory building through an opening in the roof. The rent of a mobile crane once a year is not too high.

2. Example environment: Ports

Answer 1. Quay days and handling effort

$$\frac{400{,}000\ \ TEU\ /\ year}{80\%\ \ 4000\ TEU\ /\ ship} = 125\, ships$$

$$125\, ships * 2\, days\ /\ ship = 250\ quay\, days$$

x = number of 20' containers, y = number of 40' containers; use [TEU] and [container]:

1) 400,000 [TEU] = x [TEU] + y [2 TEU] or 400,000 = x + 2y
2) 400,000 [TEU] / (1.6 [TEU / c]) = 250,000 [c] = (x + y) [c]

This solves as: x = 100,000 and y = 150,000

Answer 2. Unloading time

4000 * 80 % / 1.6 = 2000 c / ship

5 cranes / ship thus imply 400 c / crane.

1) At 800 c / day / crane, this is 400 / 800 = 0.5 day.
2) The average horizontal distance is 15 + ½ * 44 = 37 meters. The sum of horizontal and vertical distance is 50 + 37 = 87 meters. The spreader must move up and down, so the total distance is 2 * 87 = 174 meters. So the average speed is 174 / 60 m/s = 2.9 m/s = 10.44 km/h.

Answer 3. Demands on stacking area

Average number of TEU in stack is: 400,000 / 300 * 3 = 4000 / day.

Peak number of TEU in stack = 4000 * 1.5 = 6000 / day.

The surface of a 20' container is: 20' * 8' = 160 ft^2.

1 meter driving space on one side suffices, since one can use the meter on the other side associated with the next container.

Thus 20' * (8' + 1 m) = 20 * 0.3048 + (8 * 0.3048 + 1) m = 6.096 * (2.438 + 1) = 20.958 m^2.

1) With 2 over 1: 6000 * 20.958 = 125748 m^2 = 12.6 hectare
2) With 4 over 3 with average 2.3: 6000/2.3 * 20.958 = 54678 m^2 = 12.6 / 2.3 = 5.5 hectare.
3) The TEU factor does not really change that answer. It was put at 1 only to make the problem simpler to start with.

Answer 4. Berth utilisation

The different elements are:

1) The arrival rate is λ = 5,000,000 [tonne/year] / 80,000 [tonne/ship] = 62.5 [ships/year]
   The service rate is μ = 2000 [tonne/hour] / 80,000 [tonne/ship] = 1/40 = .025 [ship/hour].
2) We are tempted to take $\rho^* = \lambda / \mu$. Then the question rises as to how many hours per year we should take: 360 or 350 ? We then see: the formula $\rho^* = \lambda / \mu$. assumes no loss hours, while here we have loss hours.

3) The proper formula is: $\rho^* = \rho_T + \dfrac{L}{N * D}$

   where the theoretical utilisation is corrected for L the loss days, N the number of berths, and D the number of days per berth.

4) Applying this formula (changing days in hours):
   The capacity hours are 360 * 24 = 8640 [hours].
   Theoretical hours are 5,000,000 [tonne] / 2000 [tonne/hour] = 2500 [hour].
   Hence, utilisation is ρ^* = (2500 + 24 * 10) / 8640 = 0.31713.

5) And hence the implied service rate is μ = .0228 [ship/hour].

6) Given is the waiting time in the queue for all ships as WT = 1000 ($e^{3\rho^*}$ - 1) hours/year, and thus the waiting time here is 1580 [hour/year]. (Note: this differs from the Poisson distribution too.)

7) Total waiting time for all ships thus is: queue + service time, and is 1580 + .031713 * 8640 = 1580 + 2500 + 24 * 10 = 4320 [hour/year].

8) And this is per ship: 4320 / 62.5 = 69.12 [hour/ship] = 2.88 [day/ship]

3. Elementary Mathematics

Q1. 0.42 radians / (2 π) * 360 = 24.064 degrees.

Q2. We can take the unit circle, and find the point {Cos[.66], Sin[.66]} = {0.79, 0.613}. The slope of the line from {0, 0} to this point is tan = sin/cos = 0.776105. Basic math teaches us that the perpendicular has a slope -1 / 0.776105 = -1.28849

4. Distance and time

(Q1) First part = x = ½ a t^2 = ½ v t = .75 m, middle = x = 4 * 1.5; total 7.5 m

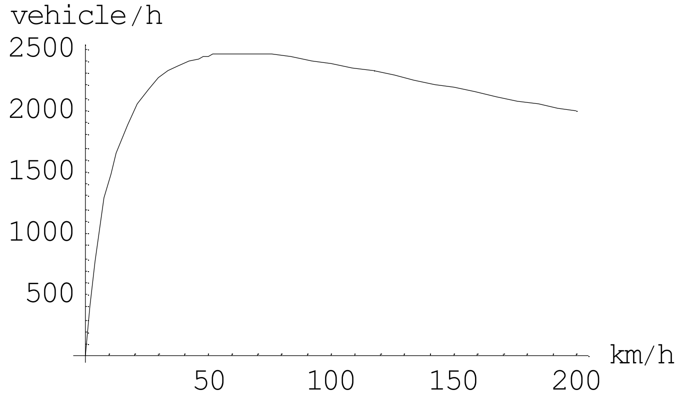
(Q2)

(a) This is actually discussed in the text: any good sequence of assumptions and substitutions.

(b) Capacity is v / (S + L). Use (a) to develop this formula (also see the body of the text). Then see the plot below (select say 4 points, 0, 200, the top - which is question (c) - and halfway between 0 and the top).

(c) Optimal capacity is .6846 vehicle/s = 2465 vehicle/hour

(d) Lower values are safer, with a limit in f = 0 (no braking).



5. Elementary Newtonian Mechanics

Answer 1: Addition of forces, 1 kg

(a) The object will move to the right along the positive horizontal axis

(b) Make the parallellogram of F3 and F5, and see that the force will be 8 N.
With F = m a, a = 8 N / 1 kg = 8 m/s^2

Answer 2: Elevator

When the elevator is at rest, F* is the normal force -G, or F* = m a = 800 N.
Acceleration is either 1.5 or -1.5.
Thus g + a is from 8.5 till 11.5 and the force is between 680 and 920 N.
(Don't forget to draw the plot.)

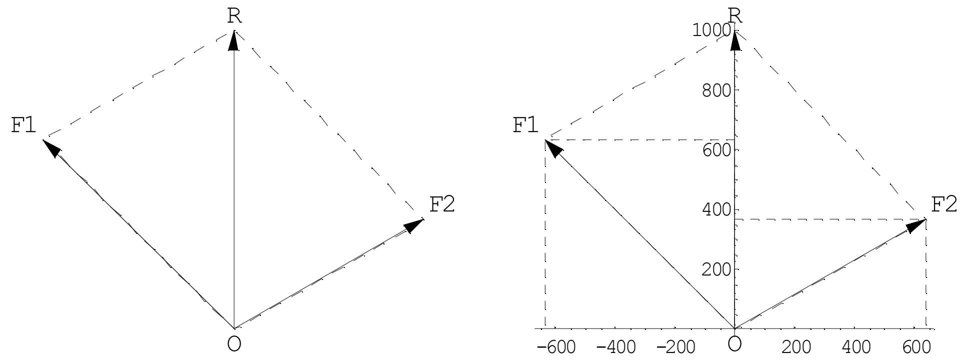
Answer 3: Addition of forces, 1000 N

We distinguish the x and y axes, and look at the angles with the x axis. The downward force of G = 1000 N meets an opposing force R, that is the resultant of the forces $F1$ and $F2$ in the ropes. The ring also is stable, so that the components of the forces that move the load to the left or to the right are in balance. Thus we find two equations:

$$F1\ \sin(45) + F2\sin(30) = R = 1000\,N$$
$$F1\ \cos(45) - F2\ \cos(30) = 0$$

Solving these gives $F1$ = 897 N and $F2$ = 732 N. The result is given in Figure 62.

Figure 62: Example addition of forces



Answer 4: Another addition of forces, 100 kg

Start with Figure 62. The forces in the rope itself now however will balance, and hence the pulley slides to the point where $T = F1 = F2$. For unknown α and β angles with the horizontal axis, we then find the two equations:

$$T\ \sin(\alpha) + T \sin(\beta) = R$$

$$T\ \cos(\alpha) - T\ \cos(\beta)\ = 0$$

The latter equation solves as $\alpha = \beta$. Thus the first equation gives $T = ½\ m\ g$ / sin(α).

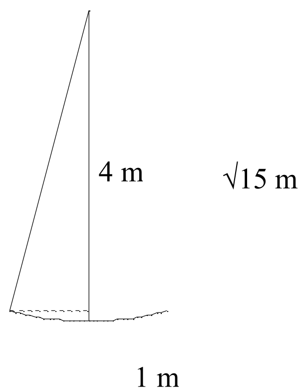
Let the pulley separate the rope in two parts $L1$ and $L2$. Then the distance between the walls gives $L1$ cos(α) + $L2$ cos(β) = 4. Using $L1 + L2 = 6$ and $\alpha = \beta$ gives cos(α) = 4/6 = 2/3. Hence sin(α) = 1/3 √5 (using Pythagoras). Hence T = 50 * 9.81 / 0.745356 = 658 N. Interestingly, it does not matter at what heights the rope is affixed at the two walls.

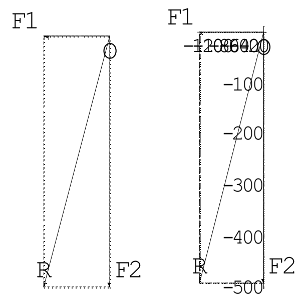
Answer 5: Another addition of forces, 50 kg

The pendular motion of the crate is depicted in Figure 63, to the left. With a radius of 4 meters and a horizontal amplitude of 1 meter, the distance from the ceiling is √15 meters (using Pythagoras). The 4 meters section of the rope makes an angle α with the horizontal plane, and tan(α) = √15. Let the tension in the rope be R. Then the gravitational force is $F2 = m\ g = R$ sin(α), while the leftward force is $F1 = R$ cos(α) = $m\ g$ / tan(α) = 126.6 N.

Figure 63: 50 kg crate

Pendular motion





Downward and leftward forces

6. Volume and Mass Flows

(Q1) One liter is 0.001 cube. The flow of 10 liter per minute means 0.01 cube / 60 s. The mass flow thus is 1/6 kg / s.

(Q2) The buffer capacity in terms of mass is $\rho\ V$. The net inflow speed is $I - O$. Hence the critical overflow moment is $t = \rho\ V / (I - O)$.

(Q3) (a) Regard grab 1, and substitute the values in the 'grab formula'. One finds $0.1\ m^3 / s = 1.5 / (1 + 1.5)\ 5000\ kg / (750\ kg / m^3\ 40\ s)$. The first grab thus fits the process. Since it is the cheapest grab, this is the optimal one. Apparently, it is more efficient since it has a lower cycle period.

(b) The bunker size follows from Vbunk = V - outflow * openperiod = V - 40. The volume of the grab is outflow * cycleperiod = .1 * 40 = 4 cube. So the bunker must be 3.6 cube.

(Q4) Pile: Area = 1444.79, Density = 0.75 t / m3, Height = 10 m, Mass = 3611.98 t, Radius = 21.4451 m, Pressure = {average 24.525, max 73.575 } kN/m2 , tan = 0.466308, Volume = 4815.97 cube.

Silo: Mass = 3611.9 (the same), Pressure = 73.575, Area = 481.6 m2, Radius = 12.4 m

Saved area = 2500 - 481.6 = 2018 m2. Also 500 * 2018 > 1 million, so silo.

7. Energy

(Q1) There is a difference: power is *work per second*. A car and a watch can do the same work, but a car will take a minute to do it, and a clock many years.

(Q2) There is no difference: we have defined power as the energy flow. We however should be aware that people often make a difference in everyday parlance. Often people use 'power' to stand for the *capacity* or the '*maximum* energy flow' that a motor can give. A car with a motor of 85 kW will give a power of 85 kW only at its maximum speed. At lower speeds it will give much less power.

(Q3) $W = 50 * g * .3 = 15\ g$. Gravity performs a work of $-15\ g$.

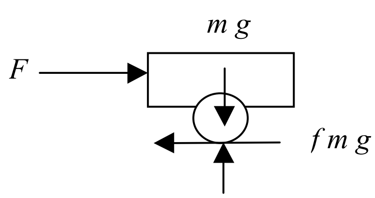
(Q4) The work is $W = 2400\ g\ 4000 = 9.6\ 10^6$ g J.
Power is $P = W / t = 9.6\ 10^6\ g / 180$ J/s = 53333.3 g J/s = 53.3 g kW.

(Q5) $P = W / t = F\ s \cos(\alpha) / t$.
The angle is always measured along the force line. Hence, even though the movement now is vertical, still $\cos(\alpha) = 1$.
Thus $P = m\ g\ s / t = 2400\ \ 10\ \ 10 / 60 = 4$ kW.
Thus a motor with a power of 4 kW would suffice to do this job, if only that the transmission would take place without loss.

(Q6) The energy flow is $P = dV/dt * \Delta p$.
$dV/dt = 250$ liter / minute = 0.250 / 60 m^3 / s.
$\Delta p = \rho\, g\, h = 1000$ kg / m^3 * 10 m / s^2 * 24 m = 240 kN / m^2.
Thus $P = 1$ kW.
The mass flow is dm/dt = $\rho\ dV/dt = 1000 * 0.250 / 60 = 25/6 = 4.17$ kg / s.

(Q7) In steps:

a.



b. $W = F\ s \cos(\alpha)$ and $\cos(\alpha) = 1$ imply $W = F\ s = f\ m\ g\ s = .08\ 60\ 10\ 500 = 24$ kJ

(Q8) Let $v_2 = v_1 + at$, so that $at = v_2 - v_1$. Also $d = v_1 t + ½\, a\, t^2$. Then:
$W = F\ d = m\ a\ d = m\ a\ t\ (v_1 + ½\ a\ t) = m\ (v_2 - v_1)\ (v_1 + ½\ \ (v_2 - v_1)) = ½\ m\ (v_2{}^2 - v_1{}^2)$.

(Q9) $G = 9.8\ 10 = 98$ N. F has a horizontal and a vertical component: $F_x = F \cos(20°) = 94$ N and $F_y = F \sin(20°) = 34$ N. The normal force N, i.e. the force exerted by the plane, is $N = G - F_y = 64$ N. (Alternatively phrased:

since the body remains on the plane, $0 = \Sigma F_y = N + 34 - 98$, and this gives the normal force $N = 64$ N.) Friction then is $F_f = .25$ N = 16 N. The law of conservation of energy gives: $½\, m\, (v_B{}^2 - v_A{}^2) = W_G + W_{Fx} + W_{Ff} + W_N$, or $½\, 10\, (v_B{}^2 - 400) = 0 + 94 * 40 - 16 * 40 + 0$. This solves as $v_B = 32$ m/s. Thus, the angle that F makes reduces its horizontal influence, but it helps to reduce the friction, and thus contributes to a greater speed.

(Q10) See Table 32.

8. Resistance

(Q1) There is a difference. The angle is φ is measured in radians on the unit circle, and then the slope is tan(φ) (as in the formula of a line) or sin(φ) (traffic).

(Q2) Roll resistance is a specific type of friction, used for vehicles. There is also air friction.

(Q3) (a) Instead of looking at a moving object that comes to rest, we will look at an object that is in rest and that starts accelerating. If an object starts from position $x(0)$ with a speed $v(0)$ and gets a constant acceleration $a(t) = a$, then:

$$v(t) = v(0) + a\, t$$

$$x(t) = x(0) + v(0)\, t + ½\, a\, t^2$$

These relationships can be verified by applying formulas $v = dx/dt$ and $a = dv/dt$.

In the situation at rest $x(0) = 0$ and $v(0) = 0$, so that:

$$v(t) = a\, t \quad \& \quad x(t) = ½\, a\, t^2$$

so that $x(t) = ½\; v(t)^2 / a$.

The force exerted on the cart is $F = m\, a$. Since action = reaction, this force equals friction. We also know that friction is proportional to the normal, with a coefficient f (now taken constant): $F_R = f\, F_N = f\, m\, g$. Setting these equal gives $a = f\, g$. Substituting this in the function for $x(t)$ gives, for start speed $v(t) = v$:

$$x = \frac{v^2}{2\, f\, g}$$

(Continued after next page.)

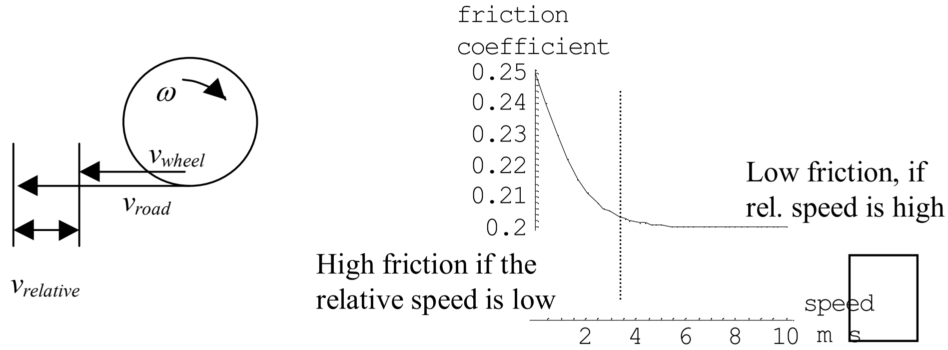
Table 32: Fuel and energy consumption for Boeing and Concorde

Concept	*Symbol*	*Example Boeing 747*	*Example Concorde*
payload	m_p	55 tonnes	12 tonnes
mass at take off [22]	m_s	350 tonnes	175 tonnes
mass at cruising	m	310 tonnes	160 tonnes
cruising speed	v	0.8 Mach = 0.8 * 295 m/s = 236 m/s = 850 km/h	Mach 2.0 = 2 * 295 = 590 m/s = 2124 km/h ([23])
transport output	T_p	$m_p\, v$ = 55*850 = 46750 tkm/h	12 * 2124 = 25488 tkm/h
lift at cruising [24]	L	= $g\, m$ = 9.8 * 310	1568 kN
air lift / drag ratio [25]	L / D	15	7.4
airfriction at cruising	D	L / 15 = 203 kN	212 kN
propulsion force [26]	T	= D	= D
SFC = specific fuel consumption	C_T	0.062 kg / (N h)	0.119 kg / (N h)
cruising fuel consumption	$T\, C_T$	= 203k * 0.062 = 12.586 t/h	25.228 t/h
cruising power	P	$T\, v$ = 203*236 = 47908 kW	212*590 = 125080 kW
heat or caloric value	H	43 10^6 J / kg	equal to Boeing
cruising energy consumption	P_f	= $H\, T\, C_T$ = 43 10^6 J/kg * 12586 kg/h = 541.2 10^9 J/h = 541.2 10^9 /3600 J/s = 150300 kW	25228 * 43 * 10^6 = 1.08 10^{12} J/h = 1.08 10^{12} / 3600 J/s = 301334 kW
cruising SEC = specific energy consumption	E_s	P_f / T_p = 541.2 10^9 J/h / (46750 tkm/h) = 11572 kJ / tkm	42370 kJ / tkm
energy efficiency	η_{TOTAL}	P / P_f = 47908/150300 = 0.32	125080/301334 = 0.42 (!)

[22] Doganis:149 discusses the maximum take off weight (MTOW).
[23] At an altitude of 16 km.
[24] At equilibrium, lift equals gravity.
[25] This ratio remains somewhat constant for different speeds.
[26] At equilibrium, propulsion equals the air friction.

(b) This essentially repeats an earlier discussion. We have seen that the friction coefficient - now not taken constant - is highest at slowest speeds. We now just need to refer to the *relative* speed. When the wheels are blocked, then the relative speed between the wheels and the road is highest, and thus the friction is lowest.

Figure 64: Friction at relative speed



(Q4) The speed is 20 m / s = 72 km / h. In Figure 37 we take the top line, and this gives an estimate of f = 0.5. Substituting the various values in the formula of question (Q3) gives the braking distance x = 400 / 10 = 40 m.

(Q5) With:

a) At the maximum $F_{Truck} = F_{Air} + F_{Roll}$. We can see that this happens at 30 m / s.

b) At 20 m / s the sum of air and roll resistance is 2.5, and the truck can produce 5.75. Thus there remains 3.25 kN for acceleration. And $a = F / m$ = 3.25 N / 50 kg = 0.065 m / s^2.

9. Momentum

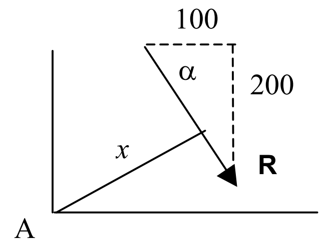
1)

(a) .1 100 9.8 - .4 N == 0 => N = 245 N
(Note: We thus find that a normal trolley is dynamically unstable, and requires an additional force to keep it up.)

(b) Move Z above A, so that N can be zero.

(c) 0.6 100 9.8 - 1.4 N == 0 => N = 420 N; F = 420 / Sin(75) = 435 N, R = 435 Cos(75) = 113 N.

(d) 25 * 9.8 = 245 N per person: 2 persons needed for F.
(Note: This is rather inefficient: better find a way to transport like in question (b) above. For example, use an additional supportive wheel. This saves a whole person, and makes the remaining one less tired.)



2) Fx = 300 - 200 = 100 N to the right

Fy = 300 - 100 = 200 N to below

$$R = \sqrt{100^2 + 200^2} = 100\sqrt{5}\ N$$

PM: Tan(α) = -200/100 = -2

$R \,.\, x$ = 300 * 0 + 300 * 4 - 200 * 1 - 100 * 1

$x = 9 / \sqrt{5}$ m

3) (a1) With respect to the origin: +F 2r - L r = 0 , so that F = L/2.
(a2) (i) W = m.g.h for both
(ii) fixed 10 m, moving 20 m
(iii) fixed would be faster but more force, moving would be less force but slower

(b1) He cannot lift himself, since his weight is 90 kg < 90+25 kg

(b2) (i) Each rope has half of the total weight: F = ½ (90+25) g = 0.56 kN.

(ii) W = m.g.h = 3 * 9.81 * 115 = 3.4 kJ

4) (a) In this case the weight does not really matter. (Perhaps only for the strength of the foundations.)
(b) The center of gravity can be found as the intersection of the lines AC and BD. The workline of gravity lies to the left of B, and in terms of momentum there is no danger of toppling.

5) (a) We apply the formula $L = X / c$ where $X = C\, b / f$. It turns out that X is the same for both cranes, namely 50. With a required reach of 5 meters, the lifted mass L is 10 t. If we substract the masses of the grabs themselves, we find no capacity for the client. Thus we have to use a more expensive method. (A bit silly, for a distance of 5 m, but such are the limits of our cranes.)
(b) Since the X's of the two cranes are the same, we may see if we can use the cheapest crane, Tom. Tom will have to lift 10 + 5 = 15 t, so the reach is 50 / 15 = 3.3 m. This is sufficient to leapfrog 1 time. In other words, the object can be moved over 5 m in two lifts.

10. Angular Motion

1) $v = 2 \pi r / T = 2 \pi\ 384\ 10^6$ m / (27.3 * 24 * 3600 s) = 1.02 km/s

2) Airplane Curve

(a) In a level flight, F = N = G = m g = 380,000 9.8 = 3.724 10^6 N

(b) (i) Now F is the composition of a sideways force S and the normal force N. Keeping N = G requires that F must be greater than G.

(ii) Tan(α) = S / N, thus S = G Tan(α) = 0.9285 10^6 N. S = m v^2/r gives v = 247.155 m/s or 889.758 km/h.

Note: More speed requires more fuel, and we even have the cube law here. Airplanes circling above airports apparently burn more fuel than in level flights.

11. Energy transmissions

1) So there are 4 transmission steps, and we get $\eta = (1 - 0.0099)^4 = 96.1\%$.

2) omegaIn = 3000 cycle / (60 Second) * 2 π / cycle = 100 π /Second;
omegaOut = 120 1000 Meter / (3600 Second) / (.25 Meter) = 133.334 /Second;
omegaIn / omegaOut = 2.35619

12. Forces and Tensions in Materials

(Q1)

a) Since $dL = F\,L / (A\,E)$ we find $F = A\,E\ \ dL / L$. With $A = 100$ mm^2 and dL / L = 1/1000, we find $F = 2.1\ 10^4 = 21$ kN.

b) The stress is $\sigma = F / A = 2.1\ 10^4 / 100 = 210$ N / mm^2

The table shows that the yield occurs at 260 N / mm^2, and **hence the application of Hooke's law was appropriate**. (This also is part of subquestion a.) But the table also shows that 175 is the maximal value. So the stress of 210 is too high.

(Q2) With $\sigma = F / A$ and $A = \pi\, d^2 / 4$ we find $d = \sqrt{(4\,F / (\pi\sigma))}$. We choose the maximal value $\sigma = 175$ N / mm^2, and find 23.4 mm. (Note: this neglects the weight multiplier.).

Answer question 1 (10 points)

Transshipment is important in transport:

1) Because it is an unavoidable step:
   a) between modes of transport,
   b) between transport and storage.
2) Because its cost/efficiency is large and affects the profitability of the transport itself

Answer question 2 (10 points)

The most important developments in transshipment have been:

1) Increase in transported volume and the size of ships and terminals.
   There has been a huge increase in the number of tonnes lifted. Larger ships are more efficient for transport. (Handling these ships increases the requirements for harbours.)
2) Increase in the speed of handling.
   It appears to be more cost/effective to increase the speed of handling equipment rather than the number of handling sites. There is a concentration of handling sites (hub and spokes systems).
3) Better adaptation of goods and equipment.
   The tools are better adapted to handling specific kinds of goods, and the goods are prepared or packaged such that they can be handled better.
   E.g. containerisation.
   By using standard container sizes that can be handled by the relevant modes of transport and transshipment terminals, there is a speed and ease of handling and transport that was not possible before for the same quantities.
4) Mechanisation and IT.
   Ever better and newer tools have been developed, and also information technology has been used, to increase efficiency.
5) From improvisation to planning.
   Due to the size of ships, waiting times are costly, and therefor scheduling is more important. Due to the huge cost of equipment, developing and installing new technology has long lead times.
6) Specialisation and phase distinction.
   Specific acts become more specialised. One example is phase distinction. Loading and unloading are different phases. In the past these could be integrated, but it has appeared that these phases could interfere with each other.

The different modes of transport have different rythms of arrival and departure, handling tools etcetera. So now there is more storage and stacking inbetween.

7) Systems approach.
Since transport and transshipment operations are more integrated, it is less easy to replace single processes and items. The systems approach helps to saveguard overall efficiency.
E.g. harbours have become more aware of the ‘landside’ part of their market. They show more interest in what happens with the goods when they leave the harbour.

8) Research: from discontinuous to continuous.
This development concerns only bulk materials. It concerns only experiments too. It has been noted that continuous methods put less strain on tools than discontinuous methods, and have a better digging profile. However, these new methods are still experimental, and the discontinuous approach still is superior.

Answer question 3 (25 points)

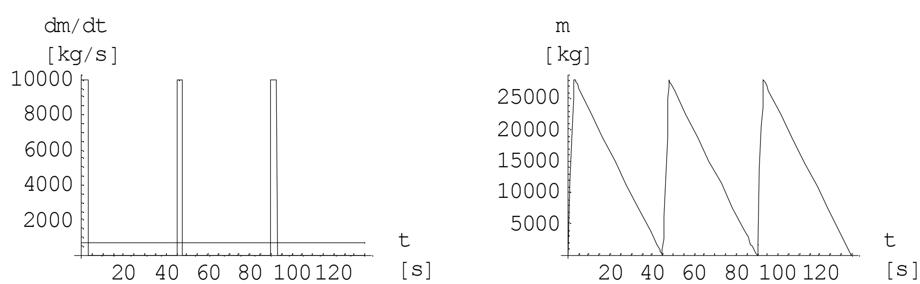
1) There are 30 tonnes load per grab, so the average number of cycles is 70,000 t / 30 (t/grab) = 2333 cycles, and the average mass outflow is *dm(out) / dt* = 70,000 t / 70 h = 1000 t/h = 277.78 kg/s.
However, we are concerned with the free digging phase. The process efficiency is 5/12, so the free digging flow is 1000 / (5/12) = 2400 t/h, and the number of crane cycles per hour in the free digging phase is 2400 / 30 = 80 c/h.

2) Cycle time is 1/80 h/c or 3600 cycles / 80 s/c = 45 seconds per cycle. Asked are 3 cyles, so we plot for 3*45 = 135 seconds.
Mass inflow is *dm(in) / dt* = 30 t / 3s = 10 t/s = 10,000 kg/s.
Mass outflow is 2400 t/h = 666.67 kg/s.
See Figure 65.

3) The minimal bunker size is 30 - 3 * 0.6666 = 28 t. In volume this is 11.2 m^3.

4) The slope in the figure on the right hand side is the mass flow *dm(out) / dt* = 666.67 kg/s. It is important, since the subsequent material handling must be able to handle this mass flow.

Figure 65: Mass flow (left) and storage (right)



Answer question 4 (20 points)

Choose a flexowell belt. See Table 33.

Table 33: Belt choice

	granular	*angle (performance for the current 60 °)*	*speed*	*tonnes per hour* [27]
normal belt	+	-	+	+
normal belt + strips [28]	+	-	+	-
flexowell	+	+	+	+
bucket elevator	+	-	+	+
sandwich belt	+	+	+	-
pipe belt	+	+	-	+

Answer question 5 (25 points)

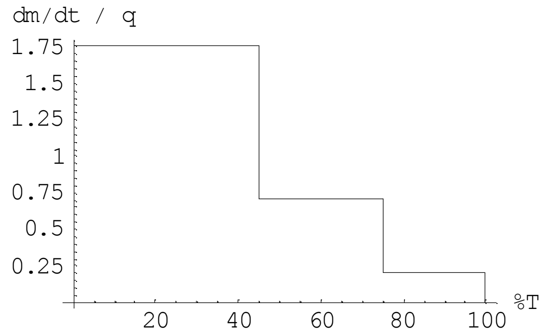
Ad a.

time	mass unloaded	dm/dt	(dm/dt) / q
T	L	$L/T = 1600$	1
0 T - .4 0T	.70 L	.7 / .4 * L/T	1.75
.40 T - .75 T	.25 L	.25 / .35 * L/T	.71
.75 T - 1 T	.05 L	.05 / .25 * L/T	.20

The result is plotted in Figure 66.

[27] Thus: tonnes per hour at the design speed. When the current angle of 60 degrees negatively affects the performance, then the column for the angle is marked with a '-'.
[28] For clarity: a 'normal belt with strips' does not have sides. It clearly is not useful for transport at larger angles. This type of belt however is included to emphasize the usefulness of the flexowell type.

Figure 66: Digging performance



Ad b. The efficiency is *q / (dm/dt)* at free digging = 1 / 1.75 = .57

Ad c. There are two cranes, so the average speed per crane is *q*/2 is 800 tonnes per hour. This is the capacity of the continuous method.

The capacity of the discontinuous method is determined by the free digging phase. Here the mass flow per crane is 1.75 *q* / 2 = 1400 tonnes per hour.

Ad d. PL / DW = 1.2. Also PL + DW = 40 tonnes. Thus PL = 21.85 tonnes.
Thus 21.85 tonnes / cycle * *n* cycle / hour = 1400 tonnes / hour implies *n* = 64. The cycle period thus is 3600 / 64 = 56.25 seconds / cycle.

Answer question 6. (10 Points)

Use the formulas in the text, for grab and pipe belt elevator. *dVd/dt* = 0.378788 cube per second.

Hence the belt width is 857 mm, and rounded 850 mm.

Fall Semester B

Answer 1: Pallet (20 points)

Regard the top box only; *m* is the top box mass. Also $F = m.g$.

1. Give $\alpha 1$ for figure 1 without a rope around the boxes.
   The Normal force is $G \cos(\alpha 1)$ so friction is $fw\, G \cos(\alpha 1)$.
   The downward force is $G \sin(\alpha 1)$.
   Stability gives $fw\, G \cos(\alpha 1) = G \sin(\alpha 1)$
   or $fw = \tan(\alpha 1)$ or $\alpha 1 = \arctan(fw)$.
2. Give $\alpha 2$ for figure 1 with a rope around the boxes.
   The Normal force now is $F + G \cos(\alpha 2)$ so friction is $fw\,(F + G \cos(\alpha 2))$.
   The downward force is $G \sin(\alpha 2)$.

Stability gives $fw\ (F + G\cos(\alpha 2)) = G\sin(\alpha 2)$
or $fw = \sin(\alpha 2) / (1 + \cos(\alpha 2) = \tan(\alpha 2 / 2)$ or $\alpha 2 = 2\arctan(fw)$.

3. Determine the ratio s = $\alpha 1/\alpha 2$.
   This ratio then is 1/2.
4. Useful properties for boxes are:
   - Be strong enough to withstand not only gravity and other loads on top, but also such rope pressures.
   - Have sides with more friction.
   - Allow attachment of ropes, to increase such friction.

Answer 2: Silo (20 points)

1. See answer sheet.
2. $\alpha = \alpha 0$ has the highest capacity, and its length is 40 / Sin(25) = 94.7 m. (Note that you might double this if you distinguish upper and lower runs. Conventionally we refer only to the spanning length.)
3. See answer sheet. (Not included here.)
4. It is not so useful to further R&D this case. The carrying capacity can be increased by running the belt faster. We are just talking about a 40 m silo. Supposedly, if the speed is at maximum and the silo requires more capacity input, then increasing the bar heights can also do the trick, with associated increase in supporting strength. The advantage of these bars is that the sliding and spillover of the grain due to girations is prevented.

Answer 3: Basic Physics (20 points)

We have no information on the mass of the ball and the angle at which it is thrown. We only have the speed and the height. Thus we use the law of conservation of mechanic energy. With E_p the potential energy and E_k the kinetic energy we find:

$$E_{pA} + E_{kA} = E_{pB} + E_{kB}$$

$$m\, g\, h_A + \tfrac{1}{2}\, m\, v_A^2 = m\, g\, h_B + \tfrac{1}{2}\, m\, v_B^2$$

Here m can be eliminated, and $h_B = 0$. Hence: $g\, h_A + \tfrac{1}{2}\, v_A^2 = \tfrac{1}{2}\, v_B^2$
Thus $10 * 15 + \tfrac{1}{2}\, 10^2 = \tfrac{1}{2}\, v_B^2$ and thus $v_B = 20$ m / s.

Answer 4: kWh (20 points)

The efficiency is 80/100 and becomes 80 / 95 = 84.2%. The savings in power are 8 hours * (100 - 95) kW = 40 kWh, or $3.6 per day. Thus the payback period is 277.8 days.

Answer 5: Cocoa (20 points)

The proper formula is $P = F\ v$ (since the force is constant, see page 56 of the handout). The force is $F = (mc + ms)\ (g + a)$ since a lift will also need to overcome gravity. Capacity must be $P^* = P\ /\ efficiency$, so after substituting the values we find: $P^* = 465$.

It turns out that B&P advised correctly, and provide the cheapest alternative. (So much for "Nomen Est Omen".)

Spring Semester A

Answer 1: Formula Review (15 points)

(a) ½ m v^2 [kg m^2 / s^2 = N m]

(b) A force F [N] at a distance r [m] from some point, exerts a momentum $M = F\ r$ [N m] on that point.

(c) Work is a form of energy, defined by: A force F [N] exerted over distance s [m], does the work $W = F\ s$ [N m].

(d) A momentum exists *at* some distance, while work is *over* a distance.

(e) In every day usage, the power of a machine is its maximal power. In physics, the power is the actual power (that may be less than the maximum).

Answer 2: Pollution (20 points)

The propulsion force equals the resistance that the car has to overcome. Substitute the various values into:

$F_w = m\ g\ sin(\alpha)\ +\ f_r\ \ m\ g\ cos(\alpha)\ +\ ½\ \rho\ \ A\ c\ v^2$

Find $F_w = 585.8$ for 100 km/h and $F_w = 755.6$ for 120 km/h, so the increase is 30%.

Answer 3: Pneumatic wheat discharge (20 points)

Set $G = m\ g = F_{air}$, and find $v = 9$ m/s or 32.4 km/h.

Answer 4: Plane (20 points)

Let the outward motors be at distance b from the center and the inward motors at distance a, all in one line. Denote $F = 90$ kN.

In the original situation the sum of the momenta around the center is $F\,b + F\,a - F\,a - F\,b = 0$.
In the new situation, one $F\,a$ falls out. The direction of the thrust is still straight forward. The center however shifts with x, so the new sum of momenta is: $F\,(b - x) + F\,(a - x) - F\,(b + x)$. This sum must also be zero. Hence, $x = a / 3$.

(Note that the question only concerns the thrust. If you include air friction, then it appears that the air friction was -4 F and remains -4 F. Hence the plane starts loosing speed and altitude. The friction remains centered at the original center too. Hence, with 3 F at a / 3 and -4 F at 0, the plane starts turning.)

Answer 5: Bike (25 points)

(a) The speed of the chain is $v = \omega r = \omega^* r^*$ so that $\omega^* = \omega r / r^*$.
Input power is $P_{in} = M_{in}\,\omega = F_{in} L\,\omega$. Output power is $P_{out} = M_{out}\,\omega = F\;R\,\omega^*$.
Thus:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{FR\omega^*}{F_{in}L\omega} = \frac{F\,R\,r}{F_{in}\,L\,r^*}$$

(b) F_{out} meets with a negative reaction force $-R_{out}$ from the chain. The momenta around the centers of crank and wheel then are:

$$F_{in}\;L\; - R_{out}\;r\; = 0 \quad \Rightarrow \quad R_{out} = F_{in}\;L / r$$

$$F\;R\; - R_{out}\;r^*\; = 0 \quad \Rightarrow \quad R_{out} = F\;R / r^*$$

Thus:

$$F = \frac{r^*}{r}\;\frac{L}{R}\;F_{in}$$

Spring Semester B

Answer 1: Formula Review (20 points)

(a) $\omega = d\varphi / dt$ [rad / s]

(b) η= Eout / Ein, a dimensionless number. While energy actually is not lost, we count the generation of heat as a loss.

(c) Work is a form of energy, defined by: A force F [N] exerted over distance s [m], does the work $W = F\,s$ [N m].

(d) A momentum exists *at* some distance, while work is *over* a distance.

(e) In every day usage, the power of a machine is its maximal power. In physics, the power is the actual power (that may be less than the maximum).

Answer 2: Propellor (25 points)

(a) $\omega =$ 340 Meter / Second / (1.2 Meter 2 Pi / Cycle) = 45.1 cycle / second
(b) $a_c = v^2 / r$, and v = ωr gives $a_c = \omega^2 r$, so that with the angular speed given, a larger r gives a larger acceleration
(c) $\varepsilon = F / (A\ E) = rho\ A\ L\ a / (A\ E) = \rho L\ a / E$
(d) sigma = F / A = $rho\ A\ L\ a / A = \rho L\ a = 0.289$ N / mm2
epsilon = sigma / E = 1.4 10(-6)
(e) much lower: epsilon < 0.2% = 0.002. (Hence no danger of rupture)

Answer 3: Breaking (25 points)

See chapter 8 question 3.

Acceleration	Distance	Duration	Friction	Gravity	Speed
4.5	56.25	5.	0.45	10	22.5
2	126.5625	11.25	0.2	10	22.5

Answer 4: Insurance rate (30 points)

(a) The stress is $\sigma = F / A = m\ g / A$ = 5000 10 / ($\pi\ d^2$ / 4) = 196 N / mm^2

(b) The strain is $dL / L = F / (A\ E)$ = 0.0936 %.

(c) The current stress is less than the yield and hence the application of Hooke's law is appropriate. No permanent deformation.

(d) The yield weight in the rack is found by $m = F / g = \sigma A / g = 260 * 81\ \pi / 10$ = 6616 kg.

(e) The table shows that 175 is the maximal value. So the stress of 196 is too high.

(f) This stress is found at 4453 kg

(g) Yes. It doesn't suffice to say that 196 is lower than 220. Perhaps the safety should be that the maximal load of 6616 or stress 260 that the insurance engineer envisages is close to 250.

Literature

The literature on operations management, logistics and transport economics presumed here is:

Alderton (1995), “Sea transport. Operation and economics”, Reed

Anderson, Sweeney & Williams (1999), “An introduction to management science”, South Western College Publishing

Ballou (1992), “Business logistics management”, Prentice Hall

Cool (1999), “The Economics Pack User Guide”, Thomas Cool Consultancy & Research, ISBN 90-804774-1-9

Doganis (1992), “Flying off course. Economics of international airlines”, International Thompson

Krajewski & Ritzman (1999), “Operations Management. Strategy and Analysis”, Addison Wesley 5th ed.

Muller (1996), “Intermodal freight transportation”, Intermodal Association of North America (IANA) and the Eno Transportation Foundation

Russell & Taylor (2000), “Operations management”, Prentice Hall

Literature used for physics is:

Timoshenko & Young, “Mechanics of materials”

Schweers & Vianen (1967), “Natuurkunde op corpusculaire grondslag”, Malmberg

L&M Educatief (1994), “Examentraining HAVO Natuurkunde 1991 t/m 1994”, Zeist

Appendix: Some interesting websites

The search engine on transport science gave 182 hits.

General cargo and special shipping links are:

http://www.cargosystems.net/

http://www.port.rotterdam.nl

http://www.eecv.nl

http://scheepvaart.pagina.nl/

http://www.guide-u.com/rotterdam/business/shipping.htm

http://www.kct.com.my/tariff.htm

http://www.drewry.co.uk/

http://www.bulk-online.com/

http://www.bulk-online.com/PHP/phpmain.htm

http://www.bmha.com/

http://www.bmha.com/terminal/mainterm.htm

http://www.bmha.com/terminal/sunloa.htm

You could also do a search on ‘flexowell’, ‘siwertell” etcetera. Sometimes machines break down spectacularly:

http://www.argonautics.com/Projects/Argo_siw.htm

The Economics Pack software contains also packages on transport science:

http://www.dataweb.nl/~cool/TheEconomicsPack/index.html

You may also be interested in doing a search e.g. on +physics +interactive. This tends to give sites with programs that allow you to do physics in an interactive way. For example, we found:

http://www.krev.com/products/ip.html (“Interactive Physics”).

We also found the “Interactive Physics Problem Set” with questions and answers on comparable issues - specifically at:

http://blue.hallym.ac.kr/Edu/IPPS/RTF_Q&AS/Contents.html

Student projects at Technical University Delft are:

http://www.wbmt.tudelft.nl/tt/logistic/rapport/raDO__LT.htm

Appendix: Study notes

(1) Former generations of students asked us to pass on this message to future generations of students: If you don't work on the sums right from the start, then you will have a hard time trying to do the exams.

(2) Students have suggested to extend the table of symbols in the back with the page numbers where the symbols are discussed. We decided not to do this, since it is a good exercise for the students themselves to find these pages (and possibly record them in the margin). You really have to understand something about the concepts before you can link the concepts from one page to the other.

(3) We also advance a warning that dimensions are rather important. Suppose that a test question concerns a transshipment area of 3.5 hectare, and you are asked to find the sides of a square area of this size. You might want to compute $\sqrt{3.5} = 1.87$. When you would give the answer 1.87, then you would fail the test. Because you forgot the dimension, and left a hidden factor of $\sqrt{\text{hectare}}$. Since a hectare is 10,000 m^2, the proper answer is 187 m. This is just a simple example of the importance of dimensions, and serious cases are more complicated.

(4) Some students wanted more sums at the exam level. Our impression is that already many sums have been provided, and that there could be some overkill. Studens should first do the sums per chapter and then later try for the integrated questions of the example exams.

(5) Since logistics students have doubts about Transport Science, we asked former students to comment on the subject. Here follow some of their reactions.

Student 1 understands what we target for:

> "I think as a Logistics Management student that Transport Science is a difficult but also useful subject in this Logistics Management course. The subject deals with the technical aspects of transport and handling systems. I think that after finishing this course that I've not the knowledge to understand all possible technical problems, but when engineers are talking about the technical aspects of a logistic system, that my knowledge is enough to know what they (to a certain level) are talking about. I think that we need this subject because in real life as a logistics manager you have to work together with all sorts of people, engineers, marketers, accountants etc. I think that negotiating with those people becomes easier when both parties understand what they are talking about. (…)"

Student 2 is critical:

> "I'm not sure what my future benefits are from Transport Science. I do believe it plays an important role in the logistics but I don't believe that I as a general logistic manager should know all the details about it since there will be specialists for this in transport science. Although it is handy for us as a

> logistics manager to know something about it. But I think then the lessons should be adapted to this. At the moment I'm learning all these great formulas but I would not have a clue when or how I will be using this in the future. A solution for this can be to give more practical examples and work with these examples instead of learning all the formulas. It is more important to understand what a specialist in general is talking about in practice than it is to know the formulas you have to apply. For example you have to know that there can be different forces on a crane and what role they can play in making your decision of what crane to buy or how to use it, but I would leave the calculations over to the specialists since they are much better at it and actually studied for it."

An answer to this student is: We try to target for your general understanding. You are presented with only a little bit of engineering, and indeed you should leave technical decisions to the specialists. We do not require you to learn the formulas, since the exam has a formula sheet. We do require you to understand the formulas, even though you will not use them again in your later life as a logistics manager. The reason for this is that understanding these formulas and using them in sums is the only way to make sure that the general understanding that we target for really sinks down into your brain. We are pretty certain that you will forget much in due time, but the basic understanding will remain as a residue. This is the only way that we can do it.

Student 3 is most critical:

> "My opinion on transport science is that the subject is too technical for a management study. And it might be useful if we got into the subject somewhat deeper, but we only learn the basics, which I think is not enough to talk to engineers in our future career. More useful would be the practical side of this subject or the mechanics of for instance the tools and equipment used in a harbor or in a company. And the formulas given are very basic and certainly not enough to talk to engineers. If this subject will be given in the future more practical examples are very welcome, because it is still not absolutely clear wherefore the different things like kinetic energy, momentum and so on are used for. But to my opinion the subject is better changed to a subject of mechanics or another logistical subject, because the present subject is neither useful nor practical."

Answers are: (a) This is a little bit the eternal discussion. Too little is not enough, too much is too much. These pages provide for very many practical situations, but we cannot limit ourselves to just that. (b) We want to stay close to practice, but then it appears that a little bit of theory helps so much to better understand things. We have tried to give here the basic concepts that *really allow* for a useful *logistics* discussion with the engineers. (c) Admittedly, we teachers failed to get this message across for this student. Perhaps we may try again, and refer him to the first chapter that discusses the basic links between operations and engineering. The rest follows from this.

Appendix: Acknowledgements

The photographs in this book have been reproduced with kind permission of European Combined Terminals BV (ECT), Seattleweg 7, Pernis, The Netherlands.

All photographs were in colour originally, but have been scanned and turned into grayscale for purposes of reproduction, while white has been added to give a subdued impression.

The photographs have originally been made by:

(a) Eric Bakker, Beschoeiing 81, NL-3191 HK Hoogvliet, tel. +31-(0)-10-4167011 (photo's on pages 26, 32, 39, 81).

(b) Photo Sea Sky Martin, West Sidelinge 198, NL-3042 CV Rotterdam, +31-(0)10-4159305 (Cover photo, and on pages 9, 16, 49, 63, 73, 94 (detail), 99, 104, 112).

Appendix: Concepts & Symbols

General physics

Concept	*Symbol*	*Unit*	*Remarks*
length	l or x	m, km, mm	h for height. Don't mix up l and 1 (one)
area	A	m^2	circle with radius r has $A = \pi r^2$; globe with radius r has surface $A = 4 \pi r^2$
volume	V	m^3	circle with radius r has $V = 4/3 \pi r^3$
mass	m	kg	differs from *kg force*
density	$\rho = m / V$	kg / m^3	mass per cube
time	t	s, h	second, hour
volume flow	dV / dt	m^3 / s	infinitesimal change of cubes per second
mass flow	dm / dt	kg / s	infinitesimal change of mass per second
place	s	m	x = distance, dx = displacement
speed	$v = dx / dt$	m / s	instanteneous displacement per second
acceleration	$a = dv / dt$	m / s^2	linear acceleration
force	$F = m\ a$	N	Newton, $N = kg\ m / s^2$
impulse		N s	
gravity	$G = m\ g$	N	with g the acceleration by gravity
pressure	$p = F / A$	N / m^2	Pa = Pascal, force per square meter
momentum of force, torque	$M = F\ l$	N m	l is the arm of the force on a point
momentum of inertia (mass)		$kg\ m^2$	
energy	E	J	Joule
work	$W = F x \cos(\alpha)$	J = N m	Joule = $kg\ (m / s)^2$
potential E	$E_p = m\ g\ h$	J	only for gravity field
kinetic E	$E_k = ½\ m\ v^2$	J	for mass m with speed v
power	$P = dW / dt$	J / s	Watt
E efficiency	η	none	$= P(out) / P(in) = E(out) / E(in)$
External W	W_u	J	the labour exerted on an outside body
Heat transfer	Q	J	

General conditions

Body in equilibrium: $\Sigma F_x = 0, \quad \Sigma F_y = 0, \quad \Sigma M_p = 0$

A closed system: $E_p + E_k + W_u + Q = \text{constant}$

In a gravity field without external labour and heat transfer:

$$E_p + E_k = \text{constant}$$

$$m\ g\ h + \tfrac{1}{2}\ m\ v^2 = \text{constant}$$

Special cases

Rotation with a constant speed (a = 0):

Concept	Symbol	Unit	Remarks
angle	$\phi = \omega t$	rad	arc on the unit circle
angular speed	$\omega = 2\ \pi n$	rad / s	thus constant
angular acceleration	α	rad / s^2	
angular impuls		N m s	
cycle		2 π rad	a.k.a. revolution
frequency	n	1 / s or Hz	Hertz, can be a fraction
bow	$x = r\ \phi$	m	with radius r
orbit speed	$v = r\ \ \omega$	m / s	
centripetal acceleration	$a_c = v^2 / r$	m / s^2	

Power for translation: $P = dW / dt = F\ dx/dt = F\ v$

Power for rotation: $P = dW / dt = F\ dx/dt = F\ v = F\ r\ v / r = M\ \ \omega$

Friction:

Concept	*Symbol*	*Unit*	*Remarks*
friction force	$F_w = \mu \ F = f \ F$	N	μ and f are used arbitrarily
friction coefficient	$\tan(\phi) = \mu = f$	none	
motion friction	$F_R = f\, m\, g \cos(\alpha)$	N	
slope friction	$F_H = f\, m\, g \sin(\alpha)$	N	
air friction	$F_L = ½\, \rho\, c_w\, A\, v^2$	N	
brake distance	$x = ½\, v^2 / (f\, g)$	m	
transmission	$i = \omega(in) / \omega(out)$	none	if i is given, $M(out) = i\, M(in)$

For pumps:

Concept	*Symbol*	*Unit*	*Remarks*
Power	$P = dV/dt \ \Delta p$	J / s	Δp is the difference in pressure that the pump must overcome

For conveyor belts:

Concept	Symbol	Unit	Remarks
mass flow	$dm/dt = \rho\, A\, v$	kg / s	
Power	$P = f\, A\, \rho\, g\, l\, v$	J / s	
pull	$e^{\mu\alpha} = F_1 / F_2$	none	
class	$K \approx 10\, F_1 / B$	N / mm	uses belt width

For steel bars:

Concept	Symbol	Unit	Remarks
strain, stretch	$\varepsilon = \Delta l / l$	none	Δl = elongation
stress	$\sigma = F / A$	N / mm^2	pull, not push (pressure)
elasticity	E	N / mm^2	Don't confuse with E energy
Hooke's law	$\sigma = E\, \varepsilon$		