Indirect energy use

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Content

Indirect energy use

The use of indirect energy can be disaggregated into two processes:

- manufacturing of transport means for the transport system (road, rail, air etc).
- construction, operation and maintenance of infrastructure for the transport system.

This document will analyze the system boundaries of indirect energy use for different transport systems, as well as the content of these infrastructures. The goal is to make the estimates for different transport infrastructures as comparable as possible and to present estimates for construction, operation and maintenance for these infrastructures.

LCA Analysis

LCA-analysis will be employed in order to analyze the use of indirect energy consumption for different transport systems. An LCA-analysis can be separated into four stages [1]:

1. Definition of goal and scope of the study. Especially important in this context is the definition of the transport system boundaries, what is to be included in the analysis and what is to be left out. Should railroad stations be included in the analysis of railway infrastructure? If yes, why not include parking houses or roadside restaurants or truck stops for road infrastructure? If no, are all relevant parts of the rail infrastructure included in the analysis?
2. Analysis of the environmental impact of a product or service through all it's life-stages, from excavation and manufacturing of materials needed for the product or process in question to it's disposal after being used.
3. Assessment of the local, regional or global effects of the use of a specific product or service.
4. Interpretation of the results of analysis by evaluating the uncertainty involved in the analysis. What new knowledge is produced and how certain is this knowledge?

An important part of LCA-analysis is to identify the different stages in the life-cycle of a specific product or process during its life-time use. This document will try to identify the different stages in constructing, operating and maintaining infrastructure for different transport systems. A transport system is organized around a specific infrastructure for its use. Road transport is defined as transport using road as infrastructure, rail transport use rails and tracks as infrastructure while air transport uses airports and runways.

An LCA-analysis can be implemented mainly in three ways:

a) Using input-output analysis. Such an analysis is implemented using a matrix combining output from an economic sector with the input required to produce that output. A sector's production output can be measured in prices and income generated by that production. An LCA-analysis can be applied in order to identify input required to produce a specific output all through the production chain of the product or service in question. The environmental impact of the production can be estimated using average emission factors pr produced output.

[1] Horvath, A. and Chester. M: Environmental Life-Cycle Assessment of Passenger Transportation, http://www.uctc.net/papers/844.pdf s 7

b) Process analysis. This form of analysis tries to quantify the use of resources at each stage in the life-cycle of a certain product or service. Instead of starting off with a produced amount, this analysis starts with each stage or process and asks what input is needed in order to complete this stage. The environmental impact is analyzed tracing the use of materials and activities (i.e. excavation, manufacturing. transport) for each input. "The process-based LCA maps every process associated with a product within the system boundaries, and associates energy and material inputs and environmental outputs and wastes with each process." [2]

c) A combination of the two models described above. This is also referred to as a hybrid LCA-analysis. The different forms of analysis can overlap or supplement each other. One form of analysis can be used to check assessments obtained in the other or uncertainty can be assessed by applying both of them in a restricted analysis for a certain activity in a certain life-stage of a product or service.

The first analysis approach is top-down based. The analysis starts off with figures from an aggregated level and tries to work itself down to a more detailed picture of input in forms of materials and activities required to generate the observed output. The required input is *deduced* from the aggregated level.

The second approach is bottom-up based. Figures at an aggregated level are obtained by *summing up* or *aggregating* figures generated by an analysis at a more detailed level.

Transport mean

The use of indirect energy for a given transport mean for a given transport system includes:

- Manufacturing of the transport mean.
    - Extraction of raw material.
    - Fabrication of material.
    - Production of parts.
    - Assembling and installation of parts in factory.
    - Disposing of transport mean.
    - Heating of factories, comfort energy.
- Service or maintenance of the transport mean. This includes fabrication of :
    - Reserve parts.
    - Tires.
    - Lubricant oil.
    - Stationary heating.

Road infrastructure

Construction

A road can be divided into three parts: 1) A tear and wear layer (bitumen), typically 10 cm for American roads, 16-25 cm for European ones. 2) A layer of supporting material (gravel, concrete). Typical values are 30 cm for American roads, 60 cm for European ones. 3) A

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[2] ibid. s 7.

strengthening layer called sub-base. This layer includes filling compound, crushed stones and gravel. Typical values are 100 cm for American roads, 150-180 cm for European ones.

Construction of road infrastructure includes the following activities:

- Movement earth, crushed stones and gravel.
- Movement of building materials.
- Digging of road track.
- Blasting.
- Stone drilling.
- Manufacturing and transport of materials (asphalt, concrete).
- Construction of bridges.
- Construction of tunnels.
- Construction of embankments for road.
- Construction of level crossings, picnic areas.
- Construction of sound protecting walls.
- Manufacturing and transport of equipment (road lighting including poles, safety barriers, fences)
- Construction of parking lots.

Operation

Road operations include support system for the infrastructure. These activities include:

- Clearing of snow.
- Salting of roads.
- Weed control, clearance of roadsides.
- Cleaning of flood barriers.
- Traffic lights.
- Road lighting, especially in urban areas.
- Ventilation and lighting of tunnels.
- Parking lot lighting.

Activities such as manufacturing and transport of materials should be included in estimates for energy use in the operational phase.

Maintenance

Maintenance consists of activities that physically change the infrastructure. Road maintenance involves the following activities:

- Disposal of materials.
- Replacement of surface layers.
- Use of construction machines in maintenance operations (including manufacturing of these construction machines).
- Marking of roads (included in maintenance and not in operations since this is not a support function, but rather a modification of road surface).
- Replacement of filling compounds and concrete for support and strengthening layers.
- Replacement and reinforcement of road embankments.

- Disposal of road materials.
- Disposal of traffic lights, lighting and ventilation devices.
- Replacement of parking lot surfaces.

It is important to note that maintenance activities are directly dependent of the use of the road. They vary with road use. Operation activities on the other hand are largely independent of road use, i.e. operation of road lighting and traffic signals is not dependant on the number of cars served by the road. Maintenance activities are dependant of the erosion of the road and of the corrosion of materials used in road construction. Carbon dioxide reacts with concrete and cause corrosion of concrete armoring layer (carbonating). Use of salt accelerates this process.

Rail infrastructure

Construction

Railway infrastructure consists of two main parts:

- Track surface or track bedding [3]
  - ballast,
  - rails,
  - sleepers,
  - base plate,
  - fortification devices.
- Track support layer or track substructure [4]
  - supporting layer,
  - bridges,
  - tunnels.

In addition, rail infrastructure comprises railway stations. They are treated differently by different authors. Heiberg (1992) keeps stations as well as workshops out of the analysis. Schlaupitz (2008) includes "the direct transport related part" [5] of railway stations in the analysis but keeps kiosks, restaurants and shops out of it. He also excludes train control and workshops. Jonsson (2005) gives estimates both with and without stations. Horvath and Chester (2008) [6] include stations in rail infrastructure, but they give separate estimates for station construction, operation and maintenance. Horvath and Chester also includes train control, station lighting, station escalators and lighting for parking lots (including collector roads) in the analysis of railway stations operations. They provide separate numbers for all these activities. In addition they give estimates for station cleaning and station maintenance which both belong to the analysis of rail infrastructure maintenance.

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[3] Spielman, M., Bauer, C., Dones, R., Tuchschmid, M. (2007): "Transport Services", EcoInvent report no 14, 2007, page 134.

[4] ibid.

[5] Schlaupitz, H.: "Energi- og klimakonsekvenser av moderne transportsystemer", Norsk Naturvernforbund Rapport 3/2008, september 2008, http://www.naturvern.no/data/f/1/24/31/4_2401_0/Rapport_250908.pdf page 7

[6] Horvath, A and Chester, M.: Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air v.2 , University of California, Berkely, http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1015&context=its/future_urban_transport

The handling of railway stations triggers questions of compatibility with other infrastructures for other transport systems. If they are included, how should roadside restaurants, gas stations or parking houses be handled for road infrastructure? Or restaurants and shops at airports for air infrastructure?

Construction of rail infrastructure involves these activities:

- Track surface:
  - Construction of rails (made of stainless steel)
  - Construction of fasteners for rails.
  - Construction of rail switches.
  - Construction of sleepers (made of concrete).
  - Construction of embankment for supporting the track.
- Track support layer
  - Blasting of rocks and earth for digging out track.
  - Movement of earth, crushed stones and gravel for bedding of tracks.
- Support systems and materials required for the infrastructure
  - Signal systems (including cables).
  - Copper wires.
  - Poles for the railway electricity distribution system.
  - Ground foundations for poles.
  - Isolators.
  - Transformer oil.
  - Electricity distribution system (with lower voltage than normal electricity distribution system).
  - Catenary (cables providing electricity from railway's own electricity distribution system).
  - Railway stations.
  - Parking lots belonging to railway stations.

Operation

- Snow clearing of track.
- Ventilation and lighting of tunnels.
- Sound protection installations.
- Installation and reinforcement of fences keeping wildlife from entering tracks.
- Lighting and heating of railway stations.
- Escalators in railway stations.
- Lighting of parking lots belonging to railway stations.
- Train control.

Maintenance

Railway maintenance involves these activities:

- Replacement of copper wires in railway's electricity distribution system.
- Replacement of rails.
  - Welding
  - Fastening device for rails.
- Replacement of sleepers.

- Replacement of switches.
- Lubrication of switches.
- Weed control by herbicides for switches.
- Disposal of materials.
- Replacement and reinforcement of track embankments.
- Disposal of track.
- Disposal of electricity distribution system, signal and communication system.
- Disposal of lighting and ventilation devices.
- Maintenance of railway stations.
- Maintenance of parking lots belonging to railway stations (surface replacement and replacement of parking lot lighting).

Air transport infrastructure [7]

The most important activities involved in air transport are taxing to runway, startup at runway, climb to cruising altitude, cruising, approaching airport, landing, taxing to terminal and traffic control at airports or other specified location.

Airports are included in air traffic system in this report. As opposed to road transport, airports are essential for air traffic in the sense that no air traffic would be possible without them. For road transport, parking houses and roadside restaurants are judged to be marginal as opposed to essential. It is possible to conceive of a road transport system without parking houses and roadside restaurants. All in all, such a definition of the system boundaries for road and air transport renders them partly incompatible with each other. This should be taken into consideration when evaluating their environmental impact against each other. Road transport will tend to be under-evaluated in terms of its total environmental impact with these system boundaries.

Construction

- Airport buildings construction
- Runway construction
- Tarmac and taxiways construction
- Parking lot construction
- Lighting system construction, including approach systems, touchdown lights, centerline lights and edge lights.
- Construction of air traffic tower

Operation

- Operation of airport service necessary for air transport:
    - luggage handling
    - check in systems
    - computer systems
- De-icing of aircrafts
- Operation of fuel distribution system for aircrafts

[7] Based on Horvath, A. and Chester, M: Environmental Life-Cycle Assessment of Passenger Transportation, http://www.uctc.net/papers/844.pdf p 12

- Operation of parking lots, parking houses and collector roads for ground traffic services for the airport.
- Operation of buses for ground traffic services.
- Electricity consumption of lighting, including approach systems, touchdown lights, centerline lights and edge lights [8]
- Ground support equipment [9]
- Parking (lighting)

Maintenance

- Maintenance of airport buildings
- Maintenance of airport runway and tarmac, replacing layers after ordinary wear and tear.
- Maintenance of traffic control buildings and systems.
- Parking (replacement of layers for parking lot and collection roads)

[8] Horvath & Chester, p 93.
[9] For a complete list, see ibid. page 94.

Empirical results

Railway Infrastructure[10]

Table 1 Rail infrastructure energy impact

Railway infrastructure			Heiberg [2]	Jonsson	Schlaupitz	BART [1]	Caltrain [1,4]
Construction	Single track	Track substructure	2 328	2 161	9 436		
		Track base	5 150	6 300	6 779		
		Tunnels			17 429		
		Bridges			10 502		
		Tunnels and bridges [12]	1 169		27 931		
		Sum	66 518		44 145		
		Track and power distribution				34 331	6 972
	Track substructure	Blasting		1300			
		Movement of earth, stones, incl. drilling. [3]		1785	16 912		
		Materials for substructure [5]			16 629		
	Track base						
		Materials for contact wires, transformers, signal system, stations, platforms, lighting, service roads [2]			9 168		
		Welding		8,5			
		Rails		3675			
		Rail fastening		575			
		Installation		757			
		Ties		910			
		Ballast		133			
		Switchers		237			
	Stations [6]			3 761		42 409	784
	Parking lot stations					8 886	1 278
Operation	Station lighting [7]					58	69
	Station escalators [7]					15	1,4
	Train control					25	126
	Parking lot lighting					342	43
	Stations and workshops			27			
	Operations excl. stations and workshops			86			
	Materials, fuel and heating, incl. tunnels and bridges (primary energy) [10]				270		
	Train control and station lighting [11]				7		
Maintenance	Total		66				
	Station cleaning [7]					1,5	
	Diesel commuter rail			139			
	Electrified railway			157			
	Demolition [8]			1			
	Single track substructure [9]				152		
	Single track support system [9]				30		
	Track maintenance					68	49
	Station maintenance					1087	8

[10] Numbers for construction in GJ/track-km, for operation and maintenance in GJ/track-km/year. For explanation of notes, see appendix.

The estimates for track substructure and track base without tunnels and bridges vary from 7300 GJ pr track kilometer (Jonsson) to 16 200 GJ/track-km (Schlaupitz) for a single track railway. These numbers are in primary energy. The Schlaupitz estimate is larger mainly because of more crushing and moving of earth and stones in order to prepare the track *substructure*. His estimate for track *base* is more in line with the other estimates. Schlaupitz' estimate for substructure is based on construction of a railway in Sweden in an area with 64% solid rock. For each meter single track railway in open air rail tracks, 70 m^3 crushing and moving of earth and stones was required. The Heiberg estimate is based on 39 m^3 pr meter. Also, Schlaupitz estimates the need for crushing and moving of earth and stones in tunnels to be between 60 and 120 m^3 for each tunnel meter and between 20 and 40 m^3 for each meter of service tunnels. These estimates are based on discretionary adjustment of the observations from Sweden. He estimates different consumption of energy in form of diesel and electricity for different railway distances (open air track, tunnel track for main tunnel and service tunnel). Corrected for the amount of tunnels pr km of railway (37 m tunnel for each 100 meter railway track), he ends up with an estimate for substructure at 16 200 GJ/track-km. We will consider this estimate to be the most well-founded of the estimates presented for rail substructure.

As mentioned, the estimates for track base (including rails, sleepers, switchers, catenary, power distribution system etc.) from Jonsson, Heiberg and Schlaupitz are more in line with each other.

For tunnels (including both track substructure and track base in tunnels) the estimate from Schlaupitz are considerably higher than the corresponding number from Heiberg measured in GJ/-tunnel-km or GJ/bridge-km. Table 2 shows the result. The estimates are unweighted which means that they measure the energy impact for one whole km of tunnel or bridge. When added to the other estimates for railway infrastructure, these estimates must be weighted by the proportion of tunnels and bridges pr km of railway track. This is done in Table 1 . Schlaupitz refers to a proportion of 37% tunnel and 9% bridge for each railway track km. In addition he uses separate estimates for crossing railway bridges with a proportion of 0,5% for ach track km. Since Heiberg does not distinguish between bridges and crossing bridges these estimates are not included in Table 2. It should be noted that the proportions for tunnels and bridges from Schlaupitz are based on new railway tracks, they are *not* based on historical values for the existing railway infrastructure. As such, they are not fully representative for the existing railway infrastructure in Norway. We have used these weights uncorrected in this report.

Table 2 Estimates for railway tunnels and bridges

Unweighted GJ/ track-km	Tunnels	Bridges
Heiberg	22 678	36 357
Schlaupitz	47 106	106 218

It is not clear from the Heiberg report which weights are used to transform the estimates for tunnels and bridges to railway track km. The report mentions historical values for tunnels, bridges and the whole railway system from Norway 1990. When these weights are applied to the numbers above, the result is slightly higher than the sum energy impact for tunnels and bridges which is actually reported in the Heiberg report [11]. The proportion of tunnels in the Norwegian railway system in 1990 was 6,5%, the proportion of bridges was 0,8%. This is considerably lower than the proportions reported by Schlaupitz, but his numbers are more representative for railway infrastructure build today.

Heiberg's estimate for tunnels and bridges is partly based on road construction and partly based on estimates from subway systems in USA. Schlaupitz' estimate is based on process analysis, on the additional requirement for crushing and movement of stone and earth in tunnel building.

Turning to bridges, the Heiberg estimate is a rough adjustment of estimates from America. The Schlaupitz estimate is based on building of a railway bridge in Sweden and two road bridges in Norway. He notes that railway bridges require slightly more energy than road bridges and adjust for this in his final estimate. Again, the Schlaupitz estimate is more process based and seems to be more representative for the Norwegian railway system.

All in all, this report will use the Schlaupitz numbers for tunnels and bridges. In addition to tunnels and bridges, we include the Schlaupitz estimate for crossing bridges. The result is shown in Table 1. In order to transform the estimates into track km we have used the weights reported by Schlaupitz. The estimate from Heiberg for sum tunnels and bridges is taken directly from her report (see footnote above). It is assumed that crossing bridges are included in her estimates. As Table 1 shows, the estimate from Heiberg is considerably lower pr track km. This result is mainly due to the lower proportions of tunnels and bridges pr railway track km used in the Heiberg report in comparison to the proportions reported by Schlaupitz.

The estimate for BART is very much larger than the other estimates. One reason for this is that the BART estimate includes power distribution system. Also, BART has a substantial amount of elevated tracks and underground tracks since BART is part of the San Francisco transport system. The numbers for Caltrain is more in line with the other estimates. It should be noted that the numbers for Caltrain and BART are calculated on basis of their passenger-miles-travelled numbers as such:

$$I_{GJ/track-km} = \frac{\frac{I_{GJ}}{PMT} * PMT * vehicle - lifetime}{track - km}$$

where I is input in form of energy consumption, PMT is passenger-miles-travelled and GJ is giga-joule. The numbers are in direct, not primary energy. The formula uses vehicle lifetime and not system lifetime. This is because the numbers used pr PMT use vehicle life-time to calculate the total numbers of PMT travelled in BART and Caltrain systems before normalizing any input on a PMT basis [12].

The track construction estimates for BART and Caltrain are obtained by a hybrid LCA-analysis involving process analysis based on historical data as well as EIOLCA, a software tool for economic input-output analysis. [13]

Turning to estimates for construction of railway stations, the estimates vary widely. Estimates for BART and Caltrain are obtained by using EIOLCA, a software tool for economic input-output analysis. BART (Bay Area Rail Transit) has an estimate which is more then 50 times bigger than the estimate for Caltrain. It should be noted that BART is part of San Francisco subway system together with MUNI (San Francisco Municipal Railway, a public transport

[11] Heiberg, table 3-11 page 60.
[12] Horvath & Chester, page 53.
[13] http://www.eiolca.net/

system for San Francisco county) [14]. BART has 43 stations of which 14 are aerial built on columns and 13 are built at ground without columns. These are simpler stations [15], with ticket machines and no further facilities such as kiosks etc. The underground stations are partly shared with MUNI (5 of total 16 underground stations) [16] . The underground stations are bigger with more facilities. Therefore BART is not directly compatible with other railway systems.

Caltrain has much simpler stations:"…two platforms are constructed at grade on the side of the tracks." [17] There are no underground stations. The estimate for Caltrain and Bart stations are based on the amount of concrete required to construct each one of them. Each BART aerial station requires 14 625 m^3 of concrete while each surface station at grade requires 12 460 m^3. Each Caltrain station requires 510 m^3 of concrete. The estimate for Caltrain is far lower pr track-km than the one for BART. A reasonable estimate for Norwegian stations would lie within this range, probably leaning towards the Caltrain side since BART is partly a subway system.

As a combination of commuter rail system and an inner-city public transit system, BART has a lot of parking facilities, probably more than a long distance railway service. In commuter systems, passengers are encouraged to park their cars and continue their travel by rail. But aside from this reservation, construction of parking lots contributes a significant part of energy consumption for total railway infrastructure. Estimates for parking lots include a 10% addition for access roads [18]. BART has 45 890 parking spaces while the corresponding number for Caltrain is 7 814. For BART, this means one parking space for every 28 000 passenger-mile travelled or approximately one for every 46 000 passenger-km travelled. Assuming that each passenger travels around half the total BART distance, this should give one parking space for approximately every 500 passenger. The same calculation for Caltrain gives one parking space for every 400 passenger. Parking estimates for BART and Caltrain are obtained by using PaLATE, a software tool for assessing life-cycle impacts of pavement construction. [19]

From this discussion it is obvious that the level for railway infrastructure estimates will be dependant on whether stations and parking lots are included or not. It is not unreasonable to assume that the energy required for stations and parking lots together for Norwegian commuter rail system are on the same level as the energy required for the whole track substructure as they are estimated by Heiberg and Jonsson in the table above. As a corollary, the definition of system borders for rail infrastructure is highly important when comparing different estimates.

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[14] "…BART is a hybrid metro-commuter system, functioning as a metro in the central business districts of San Francisco, Oakland and Berkeley, and as commuter rail in the region's suburban areas", ", http://en.wikipedia.org/wiki/Bay_Area_Rapid_Transit

[15] "Many of the original system 1970s era BART stations, especially the aerial stations, feature simplistic Brutalist Architecture", http://en.wikipedia.org/wiki/Bay_Area_Rapid_Transit

[16] Horvath, A & Chester, M.: Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air v.2, http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1015&context=its/future_urban_transport , page 57

[17] ibid, page 58.

[18] Each parking spot has an area of 330 ft2 including access roads, 300 ft2 without. Energy consumption is calculated from PaLate, a software program developed at Berkely University, http://www.ce.berkeley.edu/~horvath/palate.html , ibid. page 64.

[19] http://www.ce.berkeley.edu/~horvath/palate.html

Operation

Table 3 Energy impact of railway infrastructure operation

Process, product or material	Construction	Source
Total energy for operation exclusive railway stations and workshops. Exclusive loss of energy by converting power to lower voltage.	52 GJ/track-km/year	Jonsson, p 25
Total energy for operation exclusive railway stations and workshops. Inclusive loss of energy by converting power to lower voltage.	86 GJ/track-km/year	Jonsson, p 25 (Swedish Rail Authorities', Banvärkets, own estimates)
Total energy for operation inclusive railway stations and workshops. Inclusive loss of energy by converting power to lower voltage.	113 GJ/track-km/year	Jonsson, p 25
Railway stations and workshops	27 GJ/track-km/year	Jonsson, p 25
Railway stations (station lighting, station escalators, train control, parking lot lighting)	440 GJ/track-km/year	BART (Bay Area Rapid Transit), Horvath & Chester
Railway stations (station lighting, station escalators, train control, parking lot lighting)	239 GJ/track-km/year	Caltrain, Horvath & Chester
Materials, fuel and heating (thermal energy) , incl. tunnels and bridges (primary energy)	270 GJ/track-km/year	Schlaupitz, page 46, table 8-16 [20].

Estimates for BART and Caltrain are obtained by using process analysis with historical data from US Department of Energy, among other sources. As the table shows, the estimates for BART and Caltrain are quite a lot higher than other estimates shown. One reason for this can be the inclusion of parking lot lighting in these estimates. This item alone makes up 342 of the total 440 GJ/track-km/year for BART. Estimates for BART and Caltrain also include train control. For Caltrain, this activity accounts for 126 GJ/track-km/year.

For BART, parking lot lighting is the single most energy-demanding activity for railway operation. Lighting for accessory roads is included in the estimate. For Caltrain, train control is the single most significant activity for railway infrastructure operation. The numbers from Schlaupitz and Jonsson are not detailed to the same level as the estimates for BART and Caltrain.

Numbers for BART and Caltrain do not include activities such as snow clearing, fences for wildlife, tunnel lighting and ventilation and sound protection installations. The numbers quoted from Schlaupitz include these activities. In addition, his numbers are in primary energy and they include energy for lighting and ventilation in tunnels as well as heating. It is assumed that these figures are corrected for the amount of tunnels and bridges pr rail km.

The numbers from Schlaupitz are well in line with the numbers quoted from Jonsson. The Schlaupitz numbers are in primary energy, it is assumed that this also is the case for the Jonsson numbers. The numbers from Schlaupitz are weighted by the proportion of tunnels and bridges pr track km. Schlaupitz finds that heating is among the most significant contributors to energy impact by railway infrastructure operation, for surface tracks as well as for tunnels

[20] The numbers from Schlaupitz are weighted by proportion of tunnels and bridges pr track km. See discussion above.

and bridges. His numbers also include energy for train control systems. They do not include energy for parking lot at railway stations. Schlaupitz also gives estimates for train control and station lighting. These numbers are substantially lower than corresponding numbers from Caltrain and BART.

Summing it all up: If we include tunnel ventilation and lighting as well as heating, Schlaupitz ends up with an estimate of 270 GJ/track-km/year for railway infrastructure operation. This estimate is in primary energy. It does not include parking lots lighting. Jonsson ends up with an estimate at 113 GJ/track-km/year including stations and workshops, in primary energy. He does not explicitly state that tunnel ventilation and lighting as well as parking lots are included, so this is questionable. The numbers from Bart and Caltrain do not include tunnel ventilation and lighting, neither heating. In total, BART uses 440 GJ/track-km/year and Caltrain 239.

Caltrain and BART uses 0,044 MJ/passenger-miles travelled on parking lot lighting [21]. This corresponds to 0,0273 MJ/passenger-kilometer. In 2006 the number of passenger kilometers on Norwegian railroads was 3301 million [22] and the number of kilometers on the Norwegian single track railroad network was 3887 km [23]. Multiplying the energy impact pr passenger km from Caltrain and BART and dividing by the total amount of km on the rail network we get 23 GJ/track-km for parking lot lighting for the whole Norwegian rail network. This estimate is probably too high since Caltrain and BART are commuter rail networks and the Norwegian rail network comprises regional train as well as commuter rail. Anyhow, we add 20 GJ/track-km to the operation estimate from Schlaupitz and get 290 GJ/track-km for rail infrastructure operation including parking lot lighting.

The numbers from BART is not representative for an average Norwegian railway system. BART shares infrastructure and operation with MUNI, a subway system in San Francisco. The numbers for BART is corrected for this shared infrastructure, but still BART has the characteristics of a subway system with several underground stations.

[21] Horvath & Chester, p 69.
[22] http://www.ssb.no/aarbok/tab/tab-416.html
[23] http://www.ssb.no/aarbok/tab/tab-417.html

Maintenance

Table 4 Energy impact of railway infrastructure maintenance

Process, product or material	Construction	Source
Total energy for maintenance of diesel commuter rail in USA	139 GJ/track-km/year	Jonsson, p 27
Total energy for maintenance of electrified railway, USA	487 GJ/track-km/year	Jonsson, p 27
Total energy for maintenance of electrified railway, Canada, lifespan 25 year	157 GJ/track-km/year	Jonsson, p 27
Disposal of side tracks and utility tracks, calculated in Sweden	35 GJ/track-km	Jonsson, p 28
Total energy for maintenance, exclusive fabrication of machines and fuel	30 GJ/track-km/year	Jonsson, p 27
Energy for infrastructure maintenance for BART USA, single-track electrified commuter rail	1 157 GJ/track-km/year	Horvath and Chester page 67-69
Energy for infrastructure maintenance for Caltrain USA, single-track diesel engine driven railway train	57 GJ/track-km/year	Horvath and Chester p 27 67-69
Energy for single track substructure and support system maintenance (incl. stations)	182 GJ/track-km/year	Schlaupitz, page 41 and 42

Schlaupitz divides maintenance activities in three categories [24]:

- fuel consumption for vehicles used in maintenance activities,
- electricity and heating consumption,
- energy released from use of materials, including materials for buildings such as railway stations.

Horvath and Chester identify the following activities as essential for railroad track maintenance:

- material replacement,
- grinding (or smoothing)
- inspection.

Horvath and Chester use factors derived from SimaPro [25] to calculate the energy impact of railroad maintenance. The figure for BART is 68 GJ/track-km/year while the corresponding number for Caltrain is 49 GJ/track-km/year.

Schlaupitz ends up with an estimate of 182 GJ/track-km/year for track substructure and support system (excluding track bedding). His numbers include tunnels and bridges which is not the case for Horvath & Chester. His estimate is corrected for the proportion of tunnels and bridges pr track km. Schlaupitz includes both energy impacts from material consumption as well as energy related to vehicle use in reconstruction activities. In addition, he includes support systems in his calculations, systems that include replacements of wires and signal

[24] Schlaupitz, page 41 and 42

[25] Ref. http://www.pre.nl/simapro/

system for train control, railway station maintenance, platforms, fences, lighting and signposts.

Horvath & Chester additionally include estimates for station maintenance which include activities such as station cleaning, routine rehabilitation and reconstruction. Horvath & Chester assume a fixed percentage (5%) of initial construction impact as relevant for yearly station maintenance. Again, it should be noted that BART stations vary widely since the system is part of San Francisco municipal transit system which include a subway system with underground stations. Caltrain stations are very simple, more precisely described as “outdoor platform-type stations” [26]. Consequently, station maintenance energy for BART is about 135 times the corresponding value for Caltrain.

Heiberg gives an estimate for maintenance of Norwegian railroads of 18 380 kWh pr track-km/year which is 66 GJ/track-km/year [27]. We assume that this estimate is for single-track railway. It is not clear from the text whether Heiberg separates operation from maintenance.

All in all, for Norwegian railways it is fair to believe that the number from Schlaupitz is quite representative. The figures based on his report which are presented here do not include track bedding. Schlaupitz gives estimate for track bedding in negative numbers in order to avoid counting energy impact twice, both during construction and reconstruction. The negative numbers add up to 43 GJ/per track-km /year [28] , including tunnels and bridges. Then again Schlaupitz does not include kiosks and restaurants in railway stations which may underestimate the impact of railway stations on rail maintenance. All in all it is reasonable to believe that an estimate of 250-300 GJ/track-km/year is representative for maintenance of Norwegian railroads.

[26] Horvath & Chester, page 63.
[27] Heiberg, page 59
[28] Schlaupitz, Table 8-10, page 42.

Road Infrastructure[29]

Table 5 Energy impact of road infrastructure

				Heiberg [1]	Jonsson	Schlaupitz [1,4,5]	Horvath Chester [2]
Constr.	Road substruct.	Two lanes excluding tunnels and bridges	Building	3 752	2 694	5 364	
		Two lanes, tunnels and bridges	Building			45 032	
		Four lanes excluding tunnels and bridges	Building			18 238	
		Four lanes, tunnels and bridges	Building			87 617	
		Two lanes excluding tunnels and bridges	Materials	4 786		677	
		Two lanes tunnels and bridges	Materials			249 880	
		Two lanes rural road	Materials				521
		Two lanes urban road	Materials				646
		Two lanes rural road	Process equipment				27
		Two lanes urban road	Process equipment				33
		Two lanes rural road	Transport materials				158
		Two lanes urban road	Transport materials				195
	Road surface	Two lanes	Fuel	54			
		Two lanes	Materials excl. bridges and tunnels	3 938		3 830	
		Two lanes	Materials for bridges and tunnels			11 344	
		Two lanes rural road	Manufacturing materials				1700
		Two lanes urban road	Manufacturing materials				2103
		Two lanes rural road	Process equipment				11
		Two lanes urban road	Process equipment				14
		Two lanes rural road	Transport materials				2725
		Two lanes urban road	Transport materials				2774
	Parking						370
	Road infrastruct.	Two lanes, Sweden. Asphalt	Total		7 668		
		Two lanes tunnels and bridges, building and materials		194 400		306 256	
		Two lanes including tunnels and bridges, weighted sum		13 731		14 012	
		Two lanes Sweden, concrete surface			11 484		
		Highway, Sweden 2 lanes			12 960		
		Freeway USA 6 lanes			44 740		
Road operation		Snow clearing, road salting, road lighting			27	253 [5]	47
Maintenance	Rural road	Incl. manufacturing of machines			367		
	Highway [3]	2 lanes Sweden. 20 years life, 4000 vehicles/day			350		
	Highway	6 lanes USA concrete, 50 years life, 52800 vehicles/day			1 029		
	Highway	4 lanes Canada, 20 years life 22 000 vehicles/day			308		
	Rural road	Sweden. 2 lanes. 40 years life. Asphalt.			72		
	Rural road	Sweden. 2 lanes, including manufacturing and maintenance of process equipment			367		
	Rural road	Finland. 2 lanes. 40 years life.			66		
	City road	USA. 2 lanes. 40 years life.			123		

[29] For explanation of notes, see appendix. Numbers for construction in GJ/km, operation and maintenance in GJ/km/year.

	Standard	2 lanes, Norway			445 [4]	
	Relaying of asphalt surface		289			

Estimates for energy consumption for subbase *building* in a two lane road vary from 2 694 GJ/road-km to 5 364 GJ/road-km. These estimates exclude tunnels and bridges. The lowest estimate is based on Swedish roads, the highest on Norwegian ones. The terrain in Norway is more demanding with mountain passes and generally more hills than in Sweden. The road geometry (width and length of roads, thickness of subbase) is roughly the same.

Estimates for subbase *materials* in a two lane road vary more. Heiberg reports 4786 GJ/road-km excluding tunnels and bridges while Schlaupitz reports much less, 677 GJ/road-km. The estimates both from Heiberg and Schlaupitz include transport of materials. The Heiberg estimate also includes depreciation of machines. He also uses a road lifetime of 100 years while Heiberg uses 40 years.

Turning to road surface (wear layer) we find that the estimates from Heiberg and Schlaupitz correspond very well. Heiberg reports 3 938 GJ/road-km while the Schlaupitz estimate is 3 830 GJ/road-km.

Estimates for tunnels and bridges in road construction range from 194 400 GJ/tunnel-km in Heiberg to 306 256 GJ/tunnel-km in Schlaupitz. This includes both road subbase and surface. Some of the discrepancy in the two estimates can be explained by diverging proportions of tunnels and bridges in the road system. Schlaupitz uses an estimate of 50 m tunnels for every road-km, the corresponding number from Heiberg is 13,4. Since the Heiberg report is 16 year older than the Schlaupitz one, there is reason to believe that newer roads in Norway will generally have a larger proportion of tunnels than older ones. Also the Schlaupitz estimate is more detailed, specifying 73 m^3 of average mass excavation in two lane tunnels and an average transport distance of the excavated mass of 4000 m (page 54). Heiberg uses a factor of 3 for tunnels in comparison to ordinary road subbase. Since ordinary subbase requires 14 300 m^3 pr km Heiberg will have 42 900 m^3 of subbase excavation pr km tunnel which should be 42,9 m^3 pr meter. This difference in mass excavation will be one explanation for the divergence of estimates.

The numbers for tunnels quoted above is in tunnel-km. When we add these estimates to other road estimates, we should adjust for the number of tunnel meter pr road kilometer. We need to do this since there is not one tunnel km for every road km. The same goes for bridges. Doing this correction, we end up with 14 012 GJ/road-km from Schlaupitz and 13 731 from Heiberg. This includes both road subbase and surface.

Jonsson ends up 11 484 GJ/km for an estimate for a Swedish two-lane road. Supposedly this includes tunnels and bridges. The Swedish two-lane roads have a width of 13 m. Schlaupitz uses an estimate of 9,5 m width for Norwegian roads while Heiberg uses 6-7 meter for the same roads. The discrepancy between the two reports could be explained by changes in Norwegian road construction in the 16 year time span between the two reports. The relative distribution of energy on road surface and road subbase should be about the same for Swedish and Norwegian roads [30].

[30] See Heiberg, page 47.

American roads have a different composition of surface and subbase and they also have a different lifetime compared to European roads [31]. The subbase in European roads has a 60 cm support layer and a 150-180 cm layer of reinforcement materials such as gravel and stones. The corresponding numbers for American roads are 30 cm and 100 cm. The surface in European roads is usually a layer of 16-25 cm, for American roads the corresponding number is 10 cm. Also American roads have lifetime of 20 years while a European one should have 40 years, according to Jonsson. According to Horvath and Chester [32], a local rural two-lane American road will have a total width of 31 feet which is 9,5 meter. These numbers include width for the road shoulders. A two-lane local urban road has a total width of 11,3 meter. Heiberg [33] claims a Norwegian road is between 6 and 7 meter wide pluss road shoulders between 0,5 and 1,5 m, so about 8 meters width should be a resonable estimate for road width in Norway for a two-lane road. Norwegian roads should accordingly be fairly comparable with local rural roads in USA.

Horvath and Chester use a 10 years lifetime for American roads, which is even less then the number quoted from Jonsson. Interestingly, Schlaupitz uses 100 years lifetime for Norwegian roads. [34] This divergence in lifetime estimates will obviously have an impact on estimates of energy consumption for road construction, road operation and road maintenance.

Horvath and Chester find that the subbase for an American two-lane rural road uses 706 GJ/road-km for materials, process equipment and materials transport. The corresponding number for surface is 4 437 GJ/road-km [35]. In total, the number is 5 143 GJ/road-km for a two lane rural road. This is a low estimate compared to the estimate for Swedish roads referred to by Jonsson. This is probably due to smaller subbase and surface layers on American roads. It is not clear from the text whether the estimates from Horvath and Chester include tunnels and bridges, presumably they do *not*. They have used a pavement life-cycle assessment tool, PaLATE, developed at University of California, Berkely. If we throw in parking, their estimate raises to 5513 GJ/road-km. If we assume this estimate to be without tunnels and bridges and taking the lesser quality of American roads into consideration, this estimate is reasonable compared to Swedish and Norwegian estimates pr road km.

All in all, one kilometer of two-lane road construction in Norway is expected to use about 14000 GJ of energy, including tunnels and bridges and including energy for materials excavation and manufacturing, process equipment, building and transport of materials.

According to estimates given in Jonsson, a 6-lane American highway is expected to use about 3,8 as much energy pr road kilometer as the estimate for Norwegian two-lane roads given here. The other extreme is a one-lane Swedish forest road which uses 1475 GJ/road km. This road has no asphalt surface layer and no reinforcement layer in subbase.

Jonsson gives an estimate for earth moving of 2500 GJ/road-km. From Heiberg, fuel for earth moving is estimated to 755 000 kWh pr road km. which is 2718 GJ/road-km, excluding materials. Adding energy for subbase and surface we end up with 3758 GJ/road km for the

[31] Jonsson, page 21.
[32] Horvath and Chester, http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1015&context=its/future_urban_transport , page 28.
[33] Heiberg, page 47
[34] Schlaupitz, page 57.
[35] Horvath and Chester. Appendix B page 124.

whole road, excluding materials. This number is in primary energy, excluding tunnels and bridges.

Schlaupitz gives an estimate for energy consumption for building the road subbase which is 7,5 million kWh pr road km [36] . This corresponds to 26 921 GJ/road-km in direct energy, not primary energy. This estimate includes tunnels and bridges but is not adjusted for the proportion of tunnels and bridges per road km. Doing this adjustment yields an estimate of 4590 GJ/road-km. This estimate includes also energy for surface building, but excluding materials for road construction. All in all, roughly 4500-5000 GJ/road km should be a fair estimate for road building (subbase and surface) excluding materials, including tunnels and bridges. This represents roughly a third of the total energy consumption for building one km of road including tunnels and bridges. From this we can conclude that materials represent roughly two thirds of energy for road construction, including tunnels and bridges.

If we look at tunnels and bridges, Heiberg estimates 1250 GJ/road-km adjusted for the proportion of tunnels and bridges pr road km. The corresponding number from Schlaupitz is 4141 GJ/road-km. These estimates vary quite a lot, but the Schlaupitz one is the most detailed. Heiberg uses a rough approximation of three times more energy use pr tunnel kilometer as compared to road kilometer and twelve times more pr bridge kilometer. Giving the Schlaupitz estimate a slight advantage we can conclude that around 25% of total energy used for road construction is spent on tunnels and bridges, adjusted for the proportion of tunnels and bridges pr road km.

Summing it all up we conclude that materials for road construction are about 2 times more energy demanding than building operations, that energy for road subbase construction (both building and materials) represents about 2/3 of the total energy for road construction excluding tunnels and bridges, and that energy required for building and materials for tunnels and bridges represents ¼ of total energy consumption for road construction when we adjust for the amount of tunnels and bridges pr road kilometer. Total energy use for road construction is roughly approximated to be 14000 GJ/road-km.

These estimates include only the road itself. Parking lots, parking houses, roadside facilities such as gas stations and restaurants are not included in the estimates. These are hard to estimate pr road km. Horvath and Chester present energy use for parking distributed pr passenger miles travelled for three types of cars. These are sedan, sport utility vehicle (SUV) and pick-up truck. These categories are chosen in order to represent a typical mix of American cars. The most sold car model in each category is selected as representative for its type. For sedans, Toyota Camry is selected; for SUV's, Chevrolet Trailblazer and for pick-ups Ford F-Series is selected. It is assumed that only passenger cars use parking lots.

The following equations show the calculations performed to reach an estimate for total energy for parking lots for passenger cars.

[36] Schlaupitz, page 55.

Figure 1 Equations for calculating energy impact pr road km from data estimated pr passenger km

$$PMT_j = VMT_j * OCC_j$$

$$P_j = \frac{PMT_j}{\sum_{j=1}^{3} PMT_j}$$

$$PMT_{j-year}^{total} = P_j * PMT_{tot-pass-cars-year}$$

$$E_{j-year} = \frac{E_j}{PMT_j} * PMT_{j-year}^{total}$$

$$E_{total-pass-cars} = \sum_{j=1}^{3} \left(E_{j-year} * L_j \right)$$

The symbols are:

- j is subscript for the categories sedan, SUV and pick-up trucks.
- VMT_j – vehicle miles travelled for representative car in category j, i.e. 11 000 miles for a sedan, for one year.
- OCC_j – occupancy rate for representative car in category j .
- PMT_j is passenger-miles travelled for the representative car in category j in one year.
- $PMT_{total-pass-cars-year}$ is total passenger miles travelled by passenger cars in US 2005.
- P_j is the proportion for representative car in category j of all PMT for all three categories.
- PMT^{total}_{j-year} is total estimated passenger-miles travelled for category j for all passenger cars in this category for one year.
- E_j is the energy factor for the representative car in category j.
- E_{j-year} is the total energy for representative car in category j in one year.
- L_j is the lifetime for representative car in category j.
- $E_{total-pass-cars}$ is the total energy for all passenger cars over their lifetimes.

The sedan travels 11 000 miles pr year with a vehicle occupancy of 1,58. This yields 17380 passenger-miles travelled for each sedan. The SUV and pick-up truck travel each 11 000 miles pr year. The vehicle occupancy for the SUV is 1,74 and for the pick-up truck 1,46. This adds up to 19 140 passenger-miles travelled for each SUV and 16 060 passenger-miles travelled for each pick-up truck [37]. Summing up passenger-miles travelled for the representative car for each category gives us 52 580 passenger-miles travelled over all categories. We then calculate the proportion of this number for each category. The sedan has 0,33 of total passenger-miles travelled, the SUV has 0,364 and the pick-up truck 0,305. We

[37] Horvath and Chester, page 20.

also know that the total number of passenger-miles travelled for all passenger cars in USA in 2005 was 2 670 billion [38]. Assuming that there are only three types of passenger cars, namely sedan, SUV and pick-up trucks; we can distribute total passenger miles travelled for all passenger cars on the three types.

Additionally, Horvath and Chester give estimates for energy requirements for construction of parking lots pr passenger-mile for each category. Distributing the total passenger-mile travelled on each category and multiplying with TJ/passenger-mile travelled gives us the total energy requirement in TJ in one year which is 69 111 TJ for all US parking lots.

To calculate the total energy impact over all years we need to know the lifetime for parking lots. They differ with the type of parking lot. There are basically three types of parking lots [39]. First, we have roadside parking with a lifetime of 10 years. All in all, roadside parking lots make up 1/3 of all parking lots. Then we have surface parking lots and parking garages. Combined they make up 2/3 of all parking lots. Surface parking lots have a lifetime of 15 years while garages have a lifetime of 30 years. We do not know the distribution between surface parking lots and garages. To simplify, we consider all of them to be garages. Distributing total energy consumption for parking in one year on parking lot types and multiplying with their respective lifetime estimates, gives us total energy required for parking lots over the lifetime of all parking lots. Dividing again on total km of US roads in 2005 [40] gives us an estimate for parking in GJ/km. This number is 370 GJ/road-km. This number is probably underestimated since some passenger-miles travelled for pick-up trucks will be labeled under light trucks and not under passenger cars.

Parking lots consist mainly of asphalt and concrete. Garages are often constructed in steel. Thus, much of the energy required to build the parking lots come from fabrication of these materials. The reported estimate of 370 GJ/road-km is not negligible. It is more than half of total material requirement for road subbase reported in Schlaupitz (see table above).

Operation

Road operations include snow clearing, salting, road lighting and parking lot lighting and signal systems, tunnel ventilation and lighting. Schlaupitz also includes heating of service buildings without specifying what these are. Schlaupitz gives an estimate of 253 GJ/road-km/year for these operations.

Horvath and Chester give estimate for salting/use of herbicides to control roadside weed. Their estimate is given pr passenger-mile travelled for each representative car in categories sedan, SUV and pick-up trucks. In addition, an estimate is given pr passenger-mile for buses. The representative bus used is a 40-feet (12,2 m) urban bus with an average occupancy rate of 10,5 passenger pr trip and 42 000 vehicle-miles travelled pr year [41]. In order to convert the estimates for each car category and bus pr passenger-miles travelled to gigajoule pr km we use the method described in the equations above. In addition to passenger cars we distribute

[38] http://www.bts.gov/publications/national_transportation_statistics/2007/html/table_01_37_m.html
[39] Horvath and Chester, page 30.
[40] ibid., page 28, 2710915 miles total.
[41] ibid., page 20

all passenger-miles travelled on bus in USA in 2005 on the representative bus [42]. We do not have to calculate estimates over all lifetime for the vehicles since energy for operation is calculated pr year. According to Horvath and Chester, 70% of all US road km need salting [43], this fraction is presumably adjusted for in their estimate. We end up with an estimate for herbicides/salting of 3,7 GJ/road-km/year.

Freight transport is not included in this estimate. It is assumed that Horvath and Chester distributes all energy for herbicides/salting on passenger transport. Energy required for vehicles transporting herbicides/salt is also not taken into consideration [44]. All in all, the estimate of 3,7 GJ/road-km/year is probably less than what is required for Norwegian roads since the salting frequency is assumed to be greater in Norway and also since a greater percentage of Norwegian roads needs salting. The Horvath and Chester estimate for herbicides/salting is obtained from EIOLCA, a software tool for economic input-output analysis. [45]

Horvath and Chester also give an estimate for roadway lighting. Using energy impact pr passenger-mile for different categories of passenger cars and including bus transport, we end up with an estimate of 43,3 GJ/road-km/year. Again, it is assumed that all energy required for roadway lighting is distributed on passenger transport so that freight transport does not have to be included. Their estimate for roadway and parking lighting is obtained from a process analysis based on historical data from US Department of Energy.

Jonsson estimates energy for road operation to be 300 GJ/road-km/year for Swedish roads with lighting and signal systems while the corresponding number for roads without lighting and signal systems is 11 GJ/road-km/year [46]. Assuming that 5% of all Swedish roads need lighting, the energy for road operation is estimated to 27 GJ/km/year on average. Jonsson also gives estimates for the amount of energy required for operation of American roads. A freeway with 8 lanes requires 80 GJ/road-km/year, while a 4-lane arterial road requires 123 GJ/road-km/year. For a 2-lane rural road the estimate is 43 GJ/km/year while the corresponding number for a urban 2-lane road is 29 GJ/road-km/year.

Summing up the estimates from Horvath and Chester we get 47 GJ/road-km for herbicides/salting and roadway lighting. This is higher than the Jonsson estimate; one reason for this can be that a greater proportion of American roads need lighting and signal systems.

The estimate from Schlaupitz include more, not least tunnel ventilation, and is also for Norwegian roads which need more salting and snow clearing than American ones pr km. Schlaupitz states [47] that 100 kWh of electricity is required for one meter of tunnel. This corresponds to 360 GJ/tunnel-km/year. Not every road km is a tunnel km, but still the energy required for a tunnel goes a long way in explaining the difference between the Schlaupitz estimate for operation of road infrastructure and other estimates cited.

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[42] The total passenger-miles travelled by bus in USA 2005 is 140 910 209 377, see http://www.bts.gov/publications/national_transportation_statistics/2007/html/table_01_37_m.html

[43] Horvath & Chester, page 32

[44] ibid., page 32.

[45] http://www.eiolca.net/

[46] Jonsson, page 24.

[47] Schlaupitz, page 56.

Operations of railway infrastructure include running railway stations. None of the reports studied include parking garages, workshops or gas stations in road infrastructure operations.

Maintenance

The distinction between maintenance and operation is blurred. It is assumed that maintenance consists of activities that directly modify the physical attributes of the road, such as replacement of surface layers of asphalt or concrete. Maintenance also includes road marking, replacement of filling compounds in subbase layers, replacement of parking lot surfaces and disposal and use of process equipment for maintenance operations.

Heiberg notes that relaying of asphalt surface requires 80 250 kWh/road-km pr year which is equal to 289 GJ/road-km/year. Jonsson gives several estimates for road maintenance. They range from 66 GJ/road-km/year to 1029 GJ/road-km/year. The lowest estimate is for a Finnish 2-lane rural road while the highest estimate is for an American 6-lane freeway. The American roads have smaller subbase and surface layers than European ones. Also, they have shorter life times. For Swedish roads Jonsson gives an estimate of 72 GJ/road-km for a 2-lane rural road with asphalt surface. If we include manufacturing and maintenance of process equipment we end up with 367 GJ/road-km/year.

Schlaupitz gives an estimate of 445 GJ/road-km/year for maintenance of a 2-lane Norwegian road. Again, his numbers are higher than other estimates reported. The Schlaupitz numbers include tunnels and bridges which again explain much of the discrepancy. Also, the Schlaupitz numbers are in primary energy while the others presumably are in direct energy.

Horvath and Chester do not estimate maintenance impact of passenger cars. The reason is that "… damage to a roadways follows a fourth-power function of axle loads (weight per axle) so that generally, damage to roadways results from heavy vehicles such as trucks and buses." [48]. Since their estimates do not include freight transport, their estimate for energy required for roadway maintenance is not comparable with other estimates reported.

Infrastructure rail and road pr passenger kilometer

Before we turn to air passenger traffic, let us look at results from rail and road infrastructure pr passenger kilometer. This calculation is necessary in order to compare results from rail and road with air traffic.

Based on the discussion we have the following estimates for construction of single-track rail infrastructure:

Table 6 Estimates for construction of rail infrastructure. All numbers in GJ/rail-km

	Heiberg	Jonsson	Schlaupitz	Caltrain
Track substructure	3 238	2 161	9436	
Track base	5 150	6 300	6779	6 972 [§]
Tunnels [#]			17 429	
Bridges [#]			10 502	
Tunnels and	1 169			

[48] Horvath and Chester, page 29. For a critique of this position, see http://samferdsel.toi.no/article18737-334.html

bridges #				
Stations		3 761		784
Parking				1 278

§ Estimate for track and power distribution
# Adjusted pr rail km

We use Caltrain as the reference railway from Horvath and Chester. This railway is diesel-driven and is a commuter rail in the San Francisco Bay-area. The other railway system in this region is BART, but this system is partly a subway system and therefore not very representative for Norwegian railways. The Caltrain system has very simple stations and the energy use for stations is probably under-estimated in relation to Norwegian railways.

Based on the table above we will use 45 000 GJ/rail-km for rail infrastructure, this includes tunnels and bridges for track substructure and track base. It does not include stations or parking and is only for construction of infrastructure. The estimate is based on Schlaupitz' work.

In order to calculate the impact of parking lots for railway infrastructure, we need to know the amount of railway stations. There are 207 railway stations in Norway [49]. Caltrain has 34 stations [50]. Caltrain has a total length of 125 km railway [51], while the total railway length in Norway is 3 887 km when double track railway is subtracted. Consequently, there are one station for every 3,7 km in he Caltrain system and one for every 18,8 km in the Norwegian national rail system. Station density will influence the number of parking lots needed for Norwegian railways. The railway from Oslo to the Swedish border at Kornsjø has one railway station for every 4,3 km [52]. This is a railway through some of the densest populated areas in Norway. Still, the station density is below the Caltrain one. If we assume a station density of one for each 5 km the density is about 75% of the Caltrain one. Using 75% of the parking estimate for Caltrain, we end up with about 950 GJ/rail-km for the whole lifetime of the infrastructure.

For a two-lane road infrastructure we have these estimates:

Table 7 Estimates for construction of road infrastructure. All numbers in GJ/road-km.

	Heiberg	Jonsson	Schlaupitz	Horvath & Chester §
Road substructure	8 538	2 694	6 041	
Road surface	3 992		3 830	
Tunnels and bridges#	1 254		4 141	
Sum	13 784	12 960 ¤	14 012	5 142 ^
Parking				370

Adjusted pr road km
§ Based on a rural two-lane road
¤ Swedish 2 lane highway.
^ Does not include tunnels and bridges.

49 Wikipedia, http://no.wikipedia.org/wiki/Liste_over_jernbanestasjoner_i_Norge
50 Horvath & Chester, page 58
51 See http://en.wikipedia.org/wiki/Caltrain
52 See http://no.wikipedia.org/wiki/%C3%98stfoldbanen

Based on this table we will use 14 000 GJ/road-km which is an adjustment of the estimates from Heiberg and Schlaupitz. The estimate from Horvath and Chester does not include tunnels and bridges and American roads generally have lesser subbase and wearing layers than European ones.

It is quite a discrepancy between estimates for construction of tunnels and bridges between roads and railways. It is important to note that in general, railways are more demanding to construct than roads because there are stricter requirements for the gradient which leads to more moving of earth and stones for railways. In addition, tunnels for railways include railway tracks which require more energy than road surface. Rails alone requires 3 675 GJ/track-km according to Jonsson [53] while energy requirements for road surface materials according to Heiberg [54] and Schlaupitz is in the order of 3 900 GJ/road-km.

Also the parking estimate for road infrastructure is lower than the one for railways. This is probably attributable to the fact that there are more road kilometers to distribute the total energy for parking lots on than what is the case for railways.

For rail operation we will use an estimate of 270 GJ/rail-km/year and for rail maintenance 180 GJ/rail-km/year. Both estimates are obtained from Schlaupitz. We refer to the discussion above for the justification of using these estimates. For both road operation and maintenance we will use rough approbations of the Schlaupitz estimates which yield 250 GJ/road-km/year for road operation and 440 GJ/road-km/year for road maintenance.

This means that rail and road infrastructure use about the same energy for yearly operation while road infrastructure uses more on yearly maintenance. This is reasonable since road maintenance requires surface replacements caused by the wearing and tearing on asphalt layers. For rail infrastructure, there are no parallel surface replacement requirements.

Based on these estimates we can construct the following table:

Table 8 Energy impacts of different infrastructure activities for road and rail infrastructure.

Activity	Unit	Road	Rail#
Construction	GJ/km	14 000	45000
Parking	GJ/km	370	950
Operation	GJ/km/year	250	270
Maintenance	GJ/km/year	440	180
Lifetime		40	40
Km [55]	Year	93 247	4 114
Passengerkm	Million/year	60 575	3 442

Not including railway stations

The passenger-kilometers are for Norway 2007 and do only include domestic trips. Rail km is for 2007 and road km for 2008. To calculate energy use for rail and road infrastructure we need to distribute the infrastructure on freight and passenger transport. This has been done in

53 Jonsson, page 84.
54 Heiberg, side 48, Schlaupitz page 57.
55 See http://www.ssb.no/aarbok/emne1012.html

the following way: For road transport work tonne-km is recalculated into passengerkm [56]. Each passenger is supposed to weigh on average 86,5 kg inclusive luggage. So each passenger km is supposed to be 86,5/1000=0,0865 tonnekm. Each tonnekm is consequently 1/0,0865=11,6 passengerkm. For road infrastructure we sum up tonnekm and passengerkm for total transport work on Norwegian road in 2004 and calculate relative proportions.

Passenger transport for road infrastructure is defined as passenger transport with private cars, buses, taxis and rent cars,

For rail, we know the energy consumption for respectively freight and passenger transport from the Norwegian Railway Company (passenger) and CargoNet (freight) which is a company with monopoly in rail freight transport in Norway. [57] The numbers are as follows:

Table 9 Passenger and freight transport on Norwegian railways.

Passenger transport	Electricity driven	370850	MWh
	Diesel driven	80,654	MWh
Freight	Electricity driven	116750	MWh
	Diesel driven [58]	65 620	MWh

From the numbers above we can construct relative proportions for passenger and freight transport for both rail and road infrastructure. Using these proportions as weights, we can measure the energy impact of different infrastructures pr passenger kilometer produced by the transport means using the infrastructure. In order to calculate the impact of construction and parking pr passenger kilometer we must scale the estimates to obtain yearly impacts since passenger kilometer is measured for one year. This has been done by assuming a lifetime of 40 years for both infrastructure types. All parking energy is allocated on passenger transport.

Table 10 Energy impacts of different infrastructure activities pr passenger km for road and rail infrastructure.

Activity	Unit	Road	Rail
Construction	MJ/pass-km	0,130	1,066
Parking	MJ/pass-km	0,014	0,034
Operation	MJ/pass-km	0,093	0,256
Maintenance	MJ/pass-km	0,163	0,171
Sum	MJ/pass-km	0,399	1,526
Total passenger energy	TJ	24 190	4 442
TWh	TWh	6,7	1,2
Weights	Passenger Proportions	0,24	0,67

[56] See http://www.ssb.no/emner/01/03/10/rapp_200849/rapp_200849.pdf page17

[57] ibid., page 25 and 37.

[58] Calculated as 7200 tonn diesel=6 120 000 liter diesel with density equals 0,85 l/kg. With 38,6 MJ/liter, this yields 65620 MWh. For energi content of diesel, see http://en.wikipedia.org/wiki/Diesel_fuel#Fuel_value_and_price

As the table shows, rail infrastructure is more energy demanding than road infrastructure per passenger kilometer. It is important to note that the numbers for rail do *not* include railway stations.

Why is rail infrastructure more energy demanding pr passenger km? There are three main reasons for this:

1. Rail track base is much more energy demanding than road base. This is because rail infrastructure needs power distribution system, catenary, rails, switchers and sleepers in addition to road base. Also, rail substructure needs more crushing and movement of earth and stones because of a lower gradient requirement.
2. The proportion of tunnels pr infrastructure km is greater for rail infrastructure than for road. We have used estimates from Schlaupitz which indicate a tunnel proportion of 37% . The corresponding value for road infrastructure is 5% (50 m tunnel for each road km). Note that the Schlaupitz estimate is based on an *assessment* of new rail infrastructure rather than on *observation* of historical values for tunnels.
3. The proportion of bridges pr infrastructure km is larger for rail infrastructure than for road. Schlaupitz uses 2% bridges for road in comparison to 9% for rail infrastructure.

The table also shows that construction of parking lots both for road and rail infrastructure demands much energy. This is an element that is not negligible for either infrastructure.

Looking at total energy, we note that the total energy demand for passenger transport is about 5,4 times greater for road infrastructure than for rail. The weights used for passenger transport for rail and road indicate that more freight is transported pr kilometer road than for rail. It can be objected that roads are dimensioned by passenger traffic and not freight transport. Consequently, passenger transport should be given a bigger weight for construction of road infrastructure. On the other hand, freight vehicles are much more demanding on road surface than passenger cars.

Road and rail infrastructure is used for passenger transport both on short daily trips and longer trips made during leisure time. Using data from the national travel survey from 1998 we can distribute passenger kilometers with passenger cars, buses and railways on daily trips and longer trips. In order to do this, we must adjust the passenger kilometers travelled on different transport means for daily trips to a yearly basis. This is done by assuming that a year has 230 working days. This should adjust for week-ends and 6 week holidays including holydays like Christmas and Easter. Then the proportions of long and daily trips are calculated for cars and buses on one hand and railway passenger transport on the other. Trips with passenger cars include both trips as driver and as passenger. Taxis are included as passenger cars. Since the national travel survey in 1998 was a sample survey, each data item is weighted by the number in the population having specific attributes representative for the sampled data item.

Based on these data, we have calculated the following proportions of daily trips for road and rail passenger traffic:

Table 11 Distribution of daily trips on road and rail infrastructure.

Road	0,203
Rail	0,099

As the table shows, only every tenth passenger kilometer travelled by railway is on daily trips. For road transport, every fifth passenger kilometer travelled in on daily trips. Using these proportions as weights, we can calculate the energy impact of road and rail infrastructure on short and long trips. The following tables show the results:

Table 12 Energy impacts of infrastructure activities for road and rail infrastructure pr passenger km for daily trips.

MJ per passenger km daily trips	Road	Rail
Weight	0,203	0,099
Construction	0,026	0,106
Parking	0,003	0,003
Operation	0,0188	0,025
Maintenance	0,033	0,0170
Sum	0,081	0,152
TJ total	4 904	441
TWh	1,362	0,123

Table 13 Energy impact of infrastructure activities for road and rail pr passenger km for long trips.

MJ per passenger km long trips	Road	Rail
Weight	0,797	0,901
Construction	0,103	0,960
Parking	0,011	0,030
Operation	0,074	0,230
Maintenance	0,130	0,154
Sum	0,318	1,375
TJ total	19 285	4 000
TWh	5,4	1,1

These numbers are a recalculation of the total numbers presented earlier with proportions for daily trips and long trips as weights. Since we do not know what proportions of the road and rail kilometers are used for short and long trips, this recalculation is our best guess.

Table 12 and Table 13 show that a long passenger trip on road is almost 4 times as energy demanding on the infrastructure as a short road trip. From Table 13 we can also conclude that a long trip with rail is more than four times as energy demanding on the infrastructure as a corresponding trip on road. For short trips, a rail trip is almost twice as enegy demanding on the infrastructure as a road trip. A long trip with rail is over 9 times as energy demanding on infrastructure as a short trip with rail.

We can also calculate the energy impact pr tonne-km on rail and road infrastructure from freight transport. Table 14 shows the result. All parking is allocated on passenger transport. Total tonne-km on road in Norway 2007 was 16 313 million and the corresponding number for rail was 2 467 million [59]. Table 14 shows that the impact on infrastructure from road transport is much larger than for freight rail transport. This is because we have allocated a much larger share of the total transport work on road to freight transport. Norway has a railway net that is concentrated around the big cities. Large parts of Norway, including all area north of the polar circle, have no railway access at all. These parts often produce goods that are transport demanding, such as fish and metal for export.

Table 14 shows that it is about 2,5 times as energy demanding to construct road infrastructure as rail, measured pr tonne-km. For maintenance, the corresponding figure is more than 19 times more energy demanding for road freight transport than for rail.

Table 14 Energy impacts of different infrastructure activities pr tonne- km for road and rail infrastructure.

Pr tonne-km			
Activity	Unit	Road	Rail
Construction	MJ/tonne-km	1,519	0,618
Parking	MJ/tonne-km	0,000	0,000
Operation	MJ/tonne-km	1,085	0,148
Maintenance	MJ/tonne-km	1,910	0,099
Total	MJ/tonne-km	4,515	0,866

Infrastructure for air traffic

Infrastructure for air traffic has been studied by Horvath and Chester [60] . They studied three different aircrafts categorized as small aircraft (Embraer 145), medium aircraft (Boeing 737) and large aircraft (Boeing 747). In addition, they chose a representative airport in the USA (Dulles airport in Washington) for their study of airport infrastructure. The environmental impact for infrastructure is calculated for each aircraft by using estimates for passenger-mile travelled for each of them. In all the following calculations, it is assumed that all passenger transport work in the US is made be the three aircraft mentioned or rather by the group of aircrafts of which the three mentioned are representative. It is also assumed that Dulles Airport in Washington D.C. is representative of the top 50 airports in USA [61].

Horvath and Chester use EIOLCA, a economic input-output analysis for producing estimate for airport construction. [62] For runways and tarmacs they use PaLATE, a software tool for assessing life-cycle impacts of pavement construction. [63] Their estimate for air traffic operation is obtained from process analysis based on historical data from US Department of Energy.

The Horvath and Chester estimate is adjusted for freight transport with aircrafts. In general, the larger the aircraft, the more freight it carries. For Boeing 747 it is calculated that

[59] http://www.ssb.no/aarbok/emne1012.html
[60] Horvath, A. and Chester, M: Environmental Life-Cycle Assessment of Passenger Transportation, http://www.uctc.net/papers/844.pdf , page 98, recalculated by passenger-km by a factor of 0,6213
[61] Ibid., page 91
[62] http://www.eiolca.net/
[63] http://www.ce.berkeley.edu/~horvath/palate.html

passengers make up 83% of total weight transported. For Boeing 737 the same percentage is 96% while passengers make up 100% of all weight transported by Embraer 145.

The table below lists some empirical results from the study. The results are recalculated into mega joule per passenger-kilometer.

Table 15 Energy impacts of air traffic infrastructure activities distributed on different aircraft types.

MJ/pkm	Embraer 145	Boeing 737	Boeing 747
Infrastructure construction per passenger-kilometer per year	0,015	0,015	0,013
Infrastructure operation per passenger-kilometer per year	1,378	1,371	1,126
Infrastructure maintenance per passenger-kilometer per year	0,000035[64]	0,000035	0,000035
Km per flight	805	1368	12231
Passenger per flight [65]	34	94	305
Number of trips pr year	912	1895	40
Number of trips per day	2,5	5,2	0,1
Number of passengers pr year	31 018	178 170	12 161
Aircraft-km travelled pr year	734 701	2 752 489	489 114
Mill. passenger-km travelled pr year [66]	24,1	262,7	149,1

The table shows that the smaller the aircraft, the larger is the burden on the infrastructure. This is due to the fact that smaller aircrafts perform more landings and take-offs. Cruising at high altitude has no impact on use of infrastructure; therefore larger aircrafts with longer cruising distances will have a less burden on air traffic infrastructure.

Horvath and Chester chose Dulles Airport in Washington as a representative US airport. Norway has only one airport that can be compared to Dulles. Gardemoen Airport in Oslo served 19 million passengers in 2007. Dulles served 24,7 million passengers the same year. Dulles has four runways with concrete surface, the shortest is 2685 meter while the longest is 3505 [67]. Gardemoen has two runways with asphalt surface, the longest is 3600 meter while the shortest is 2950 m [68]. Dulles occupies 54 km^2 of land while Gardemoen occupies 13 km^2. Gardemoen is thus a smaller airport than Dulles. No other airport in Norway comes close. The second biggest airport in Norway, Flesland Airport in Bergen, served 4,8 million passengers in 2007 [69]. Flesland Airport had 99 172 flights that year, Gardemoen had 230 984. Dulles Airport had between 1000 and 1200 flights “on a typical day” the same year. If we consider two/thirds of all days in a year to be “typical” we end up with 245 days. Using the middle value of 1100 flights per typical day this yields about 270 000 flights in 2007.

In order to compare these estimates with other estimates we need to calculate the energy impact pr trip and pr passenger. Number of trips are calculated from information about vehicle miles travelled (VMT) in one year. We calculate the total VMT for each aircraft in

[64] Includes only airport maintenance. Same number used for all aircrafts.
[65] Horvath & Chester, page 84
[66] Aircraft km and passenger-km travelled are calculated from energy impact of airport construction. Therefore, passenger-km can not be entirely decomposed into trips, passenger pr trips and km pr trip.
[67] http://en.wikipedia.org/wiki/Washington_Dulles_International_Airport
[68] http://no.wikipedia.org/wiki/Gardermoen_flyplass
[69] http://no.wikipedia.org/wiki/Bergen_lufthavn,_Flesland

one year and divide by average flight length which is given [70]. The number of VMT for each aircraft type is calculated from the amount of GJ needed to construct the aircraft [71]. Divided by the aircraft's lifetime [72] we find the number of GJ required to construct the aircraft for each year the aircraft is in operation. The impact of aircraft construction pr VMT pr year is given, so dividing the total energy for one year by the impact pr VMT gives the amount of VMT for one year for the aircraft in question.

Let us take an example. It requires 215 500 GJ [73] to construct the Boeing 737. Its lifetime is 30 years. This amounts to 7 183,3 GJ per year for each year the aircraft is in operation. Measured pr VMT (vehicle-miles travelled), the energy required is 4200 KJ/VMT. Since vehicle miles travelled are measured for one year, dividing the energy impact of aircraft construction for one year by the energy impact pr VMT should give the VMT. Since the impact pr VMT is given in KJ we divide by $1x10^6$ to get the estimate in GJ/VMT. Dividing 7 183,3 by 0,0042 gives a VMT estimate of 1,710 million miles or 2,75 million kilometers pr year.

The estimate for air infrastructure construction can be decomposed as follows [74]:

Table 16 Energy impacts of infrastructure activities pr passenger km for different types of aircrafts.

MJ/passenger-km Construction	Embraer 145	Boeing 737	Boeing 747
Airport	0,001	0,001	0,001
Runways	0,003	0,003	0,003
Tarmacs	0,009	0,009	0,007
Parking	0,002	0,002	0,002
Sum	0,015	0,015	0,013

In total, this yields 0,0144 MJ/passenger-km for air infrastructure. As we can see from the table above, construction of tarmacs is the most energy-requiring construction followed by construction of runways. The construction of the airport itself is the least energy-requiring activity. Tarmacs are defined as "parking and staging areas near terminals, end of runways, and support facilities" [75]. According to Horvath and Chester, runways are designed to accommodate the most demanding aircraft landing at the airport. The top 50 airports in US have on average of 3-4 runways and they can all accommodate landing and take-off of the biggest aircraft. The estimate for runways and tarmacs are made with the software PaLATE, a software for assessing life-cycle inventories for pavement [76].

Horvath and Chester include estimates for car parking lots both in estimates of construction and maintenance activities. We have included the entire estimate for parking lots in the construction estimate. This means that part of the parking estimate presented here will be attributable to maintenance activities. Dulles airport has 25 000 parking spaces. The parking lot has two surface layers of 8 cm each and a subbase layer of 15 cm. Access roads are

[70] Horvath & Chester, page 84.
[71] ibid., page 90.
[72] ibid., page 84.
[73] ibid., page 90.
[74] ibid., page 90 recalculated into pkm by multiplying with km/mile=0,62137119 .
[75] ibid., page 92,
[76] http://www.ce.berkeley.edu/~horvath/palate.html

included in the parking estimate. The parking lot has a lifetime of 10 years. In comparison, Oslo Airport has 12 200 parking spaces, 5 400 of them are in parking houses.

Schlaupitz gives an estimate of energy requirements for air traffic infrastructure more adjusted to Norwegian airports. The following table shows the difference between the Schlaupitz' estimate and the one from Horvath and Chester based on US airports.

Table 17 Energy impacts pr passenger km and pr passenger for air traffic infrastructure.

	Embraer 145	Boeing 737	Boeing 747	Weighted sum	Schlaupitz
MJ/passenger-km	0,015	0,015	0,013	0,0144	
Pkm weight	0,055	0,603	0,342	1	
MJ pr passenger	11,8	22,5	156,2		
kWh pr passenger	3,3	6,2	43,4	18,8	0,39

We use weights to calculate the total energy impact of air passenger traffic pr passenger kilometer and pr passenger. The weights are constructed by dividing passenger kilometers travelled on each aircraft by the total passenger-kilometers travelled on all of them.

There is quite a large difference between the estimates on a pr passenger basis. The estimates for the US airports are almost 50 times higher than the Schlaupitz estimate which is mostly based on an estimate for Landvetter airport in Gothenburg. The requirement for materials in the Schlaupitz estimate is based on road construction, but he has "... halved the requirement for reinforcement layer" [77] for tarmacs compared to road construction. There is no justification for this action.

The Horvath & Chester estimate for runways and tarmacs is based on PaLATE which is a software package designed to be used in road construction. According to the authors, "…roadway construction is fairly different from runway, taxiway, and tarmac construction. Higher grade materials and additional processes are employed in airport construction that are not used in roadway construction." [78] For airports, Horvath and Chester have used an input-output analysis with total cost of the top 50 airports in USA as input. The Schlaupitz estimate is not based on runways accommodating the biggest aircrafts, as is typical for US airports. His estimate is more typical for Norwegian airports except for Gardemoen Airport in Oslo. This explains some of the difference in the estimates, but probably not all of it.

Another factor for explaining the difference in estimates is the inclusion of support facilities in the tarmac estimate from Horvath and Chester. Hangars and workshops are explicitly excluded from the Schlaupitz estimate [79]. In addition, he has excluded restaurants, cafes, collector roads as well as parking lots. These are included in the estimate from Horvath and Chester. Also, Schlaupitz reviews resource consumption in a "100 years perspective" [80], while Horvath and Chester uses 30 years for *aircraft* lifetime. All in all, this goes a long way in explaining the differences in the estimate.

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[77] Schlaupitz, H.: "Energi- og klimakonsekvenser av moderne transportsystem", Norges Naturvernforbund, Rapport 3/2008, http://www.naturvern.no/data/f/1/24/31/4_2401_0/Rapport_250908.pdf page 68.
[78] Horvath & Chester, page 92-93.
[79] Schlaupitz, page 68.
[80] ibid., page 69.

Heiberg refers an estimate from 1979 of 3,54 kWh per passenger [81] . This estimate is based on two types of aircrafts, a Fokker F28 with 79 passengers and a DC9 with 125 passengers. The aircrafts cover air flights from 300 to 900 km with a yearly total of 3 million passengers. The estimate is based on an aircraft lifetime of 45 years. Only runways and taxiways are included in the estimate. With a medium flight distance of 500 km, Heiberg refers to an estimate of 0,007 kWh pr passenger kilometer which is equal to 0,0252 MJ/passenger kilometer. Compared pr passenger her estimate is smaller than the Horvath and Chester one which is reasonable given that only two types of aircrafts are considered and airports are not included in the estimate. Measured per passenger kilometer her estimate is bigger than the one given in Horvath and Chester which again makes sense since the aircrafts in Heiberg's estimate travel shorter distances with less passengers.

Heiberg also refers to some other estimates. According to Irwin [82], construction of runways and taxiways without airports is estimated to 0,030-0,036 kWh pr passenger kilometer, which translates into 0,108-0,13 MJ/passenger kilometer. Calculated pr passenger, the same estimate is in the range of 12-43,2 kWh/passenger. Compared pr passenger kilometer, this estimate about 7-9 times higher than the estimate given in Horvath and Chester, even though they include airports in their estimate. Compared pr passenger, the estimate from Horvath and Chester is in the middle of the range referred to in Heiberg. This tells us that the Horvath and Chester estimate is based on transport work estimated in total passenger kilometers which is much higher than the estimate referred to in Heiberg. Considering that this last estimate is from Canada in 1979 this makes sense. Bigger planes and longer distances can be one key explanation factor for the difference between this estimate and the one from Horvath and Chester.

Operation

Horvath and Chester also estimate operation of air traffic infrastructure. Their estimate is a process analysis based on historical data from different US government agencies. Operations include lighting electricity, deicing fluid production and, most significantly, ground support equipment. Lighting systems include approach systems, touchdown systems, centerline lights and edge lights. [83] Estimate for deicing fluid production is made with input-output analysis (EIOLCA) and based on chemical products which include ethylene or propylene glycol-based fluid which is the basis for deicing operations. Ground support systems comprise 22 categories which include among others aircraft pushback tractor, ground power unit, cargo loader, deicer, buses, service truck, water truck, baggage tug, conditioned air unit and air start unit. All in all, some 45 000 vehicles in the US airport fleet can be categorized as ground support equipment.

Table 18 Energy impacts of air traffic infrastructure operations.

MJ/pkm	Embraer 145	Boeing 737	Boeing 747
Runway lighting	0,093	0,090	0,076
Other electricity	0,000	0,000	0,000
Deicing fluid production	0,145	0,142	0,117
Ground support	1,140	1,140	0,933

[81] Heiberg, page 63.
[82] Quoted in Heiberg, page 63.
[83] Horvath & Chester, page 93.

equipment			
Sum	1,378	1,371	1,126

The table above shows estimates for annually air traffic infrastructure operation activities. The first observation is that energy impact from air traffic infrastructure *operation* is bigger than the energy impact from air traffic infrastructure *construction*.

Operation of ground support equipment is by far the greatest contributor while runway lighting is the smallest. It is also worth noting that the biggest aircraft makes the least contribution on ground support equipment. This is because the biggest aircraft spend more time cruising at high altitude while the number of landings and taking-offs are higher for the smaller aircraft which consequently have more impact on ground support equipment. If we weigh each aircraft according to it's contribution to total passenger kilometers travelled for the three aircrafts, the weighted sum for all operational activities is 1,29 MJ/passenger-kilometer/year. Calculated pr passenger, this is 6002,5 MJ/passenger or 1667,4 kWh pr passenger.

Schlaupitz gives an estimate for operation of Norwegian air traffic infrastructure. He includes ground support equipment (not further specified), deicing and fire exercises. He ends up with an estimate of 7,7 kWh/passenger/year in primary energy. His estimate for operational activities is also higher than the corresponding one for infrastructure construction, but far less than the Horvath and Chester estimate. Again, part of the discrepancy can be explained by difference in the size of American and Norwegian air traffic. Also, Schlaupitz does not include lighting system in his estimate for air traffic infrastructure operations. This contributes about 6-7% of total energy impact in the Horvath and Chester estimate.

Schlaupitz has done a process analysis for his estimate. He has tried to separate transport related activities from activities that are not transport related since he does not include restaurants, cafes and service facilities in his air traffic infrastructure. He makes a discretionary assessment of total activities at Flesland Airport (the second biggest in Norway) and finds that 80 percent of them are transport related. [84]

Heiberg refers to an estimate of operation of air traffic infrastructure from Cordi on 4,8 kWh pr passenger [85]. This is also far less than the estimate given in Horvath and Chester. The size of the airports included in the calculations again explains probably most of the discrepancy in estimates. Cordi's estimate referred to in Heiberg do not include the biggest aircrafts. The top 50 airports in the USA are designed specifically for the biggest aircrafts which is the Boeing 747 in the Horvath and Chester estimate. Heiberg also refers to an estimate from Irwin in the range of 2,4-7,2 kWh pr passenger based on 20 years lifetime.

Maintenance

Maintenance of air traffic infrastructure is also estimated in the Horvath and Chester report [86]. Because of lack of data, they assume that the energy requirement for air traffic infrastructure

[84] Schlaupitz, page 69
[85] Heiberg, page 64.
[86] ibid., page 95.

maintenance is 5% of total construction requirements. This proportion of total construction impact is meant to cover material replacement needed for air traffic infrastructure each year.

Table 19 Energy impacts of air traffic infrastructure maintenance.

MJ/pkm	Embraer 145	Boeing 737	Boeing 747
Airports	0,000035	0,000035	0,000035

As the table above shows, the energy impact of maintenance is far smaller than for construction and operation. Horvath and Chester include only maintenance of airports, not of runways and tarmacs. Since the energy impact is equal for each aircraft category, the weighted sum for all aircrafts will also be 0,000035 MJ/passenger-kilometer.

Based on the estimates from Horvath and Chester, we can construct the following table. The weights used in calculation of the weighted mean are each aircraft's share of the total number of passenger kilometers transported by all of them together.

Table 20 Energy impacts of air traffic infrastructure activities pr passenger km and pr passenger.

Total weighted sums	MJ/pr passenger km	kWh pr passenger
Construction	0,014	18,8
Operation	1,288	1667,4
Maintenance	0,000035	0,05044
Total	1,302	1686,2

As the table shows, operation is by far the activity with the biggest energy impact when we consider air traffic infrastructure. Operation of the infrastructure has an energy impact which is almost 90 times as high as the construction of the infrastructure. Maintenance of the infrastructure has a negligible energy impact compared to the other activities.

The table below sum up the estimates from three different sources. All estimates are in kWh per passenger. As the table shows, the estimate from Horvath and Chester is much bigger than the other estimates. This is mainly due to their estimates of operation of air traffic infrastructure. The biggest contribution to their estimate of infrastructure operation comes from operation of ground support equipment. The key question is therefore whether the other estimates include this equipment and what kind of equipment is included. This is impossible to tell from the estimates referred to in Heiberg. Schlaupitz has included ground support equipment in his estimate, but it is not clear what equipment is included. Also, Schlaupitz has separated activities that are not transport related from the ones which are. This is done discretionary. This separation is not done in Horvath and Chester's estimate which also is based on far bigger airports than what Schlaupitz estimate is based on.

Table 21 Energy impacts pr passenger for construction and operation of air infrastructure.

kWh pr passenger	Heiberg	Schlaupitz	Horvath & Chester
Construction	3,5	0,4	18,8
Operation	4,8	7,7	1667,4
Sum	8,3	8,1	1686,2

Total infrastructure energy use

From the discussion above, we can construct the following table for different transport infrastructures. We have split the energy impact on construction, operation and maintenance. We should stress the fact that the air traffic infrastructure is based on estimates from Horvath and Chester which are designed to be representative for the top 50 airports in USA. The estimates for road and rail are more adjusted to Norwegian conditions. As such they may not be entirely comparable. It should also be noted that railway stations are not included in the estimates for rail infrastructure. Also, a lifetime of 50 years is assumed for airports [87].

MJ Pr passenger- km	Road	Rail	Air
Construction	0,130	1,066	0,014
Operation	0,093	0,256	1,288
Maintenance	0,163	0,171	0,00004
Parking lot construction	0,014	0,034	0,002
Sum	0,399	1,526	1,304

As the table shows, rail infrastructure is the most energy demanding when we look at the total energy impact. If we look at each infrastructure component, we find that for construction, rail infrastructure is also the most energy demanding. Rail has a greater energy impact than road for every component listed, even for parking. For maintenance though, rail and road are almost equal, maintenance is a very energy demanding infrastructure activity for road infrastructure. Air traffic infrastructure is the least energy demanding to construct but by far the most energy demanding to operate.

Emission of CO2

In this section we will look at emission of greenhouse gases that comes from construction of different infrastructures. There are several greenhouse gases – what they have in common is that they contribute to global warming. The most important ones are carbon-dioxide, methan and nitrous-oxide ("laughing-gas"). They have a global warming potential (GWP) 88. In order to evaluate the warming potential of different greenhouse gases they must be normalized. This means that we must measure how much they contribute to global warming on a common denominator. Usually this common denominator is CO2. So for gases other than CO2 we must know their warming potential relative to one unit of CO2.

This normalization is done by IPCC, the climate panel of the United Nations. In order to normalize, a time span must be chosen. This is because different gases decay differently over a specific time period. Accordingly, we must choose a time span over which to identify the global warming potential of each of them.

[87] Horvath and Chester, page 91. We have used their estimate for each aircraft measured pr passenger miles travelled in order to construct an estimate for airport construction. The result is an estimate of yearly impact of airport construction. Implicitly, a lifetime of 50 years is used in order to produce these estimates.
[88]See http://en.wikipedia.org/wiki/Global_warming_potential

The values presented here are normalized by the authors of the report cited. We will refer to two reports used above. Schlaupitz [89] refer to the IPCC calculation of a 100 year time span for GWP calculations. Horvath and Chester [90] do not mention which time span is used for their GHG (greenhouse gases) calculations. The choice of time span will influence the calculations since different gases will have a different warning potential due to their different decay period.

Table 22 shows emission of CO_2-equivalents from rail infrastructure construction, operation and maintenance. The table is a variant of Table 1 which presented estimates for energy use, but Table 22 is only based on the two reports mentioned. The other reports cited in Table 1 do not contain any calculation of CO_2-emissions following from their infrastructure estimates. The system borders are the same in the two tables. The estimates of emission of CO_2-equivalents for tunnels and bridges are weighted by the proportion of tunnels and bridges pr rail km.

[89] Schlaupitz, H.: "Energi- og klimakonsekvenser av moderne transportsystemer", Norsk Naturvernforbund Rapport 3/2008, september 2008, http://www.naturvern.no/data/f/1/24/31/4_2401_0/Rapport_250908.pdf

[90] Horvath, A and Chester, M.: Environmental Life-cycle Assessment of Passenger Transportation: A Detailed Methodology for Energy, Greenhouse Gas and Criteria Pollutant Inventories of Automobiles, Buses, Light Rail, Heavy Rail and Air v.2 , University of California, Berkely, http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1015&context=its/future_urban_transport

Table 22 Emission of CO2-eqivalents from rail infrastructure construction

tonne cO2-ekvivalents railway infrastructure			Schlaupitz	BART	Caltrain	
Construction	Single track	Track substructure	626			tonne CO2-equiv./ track-km
		Track base	507			tonne CO2-equiv./ track-km
		Tunnels	1 409			tonne CO2-equiv./ track-km
		Bridges	832			tonne CO2-equiv./ track-km
		Tunnels and bridges [12]	2 241			
		Sum	3 374			tonne CO2-equiv./ track-km
		Track and power distr.		3 231	639	tonne CO2-equiv./ track-km
	Track substructure	Movement of earth, stones, incl. Drilling.	3 581 #			tonne CO2-equiv./track-km
		Materials for substructure	1 620			tonne CO2-equiv./ track-km
	Track base	Materials for contact wires, transformers, signal system, stations, platforms, lighting, service roads	729			tonne CO2-equiv./ track-km
	Stations [6]			4 241	78	tonne CO2-equiv./ track-km
	Parking lot stations			586	87	tonne CO2-equiv./ track-km
Operation	Station lighting [7]			4	5	tonne CO2-equiv./ track-km/year
	Station escalators [7]			1,1	0,1	tonne CO2-equiv./track-km/year
	Train control			1,9	9	tonne CO2-equiv./ track-km/year
	Parking lot lighting			24,9	3	tonne CO2-equiv./ track-km/year
	Materials, fuel and heating incl. tunnels and bridges (primary energy)		14			tonne CO2-equiv./ track-km/year
Maintenance	Station cleaning [7]			0,1		tonne CO2-equiv./ track-km/year
	Single track substructure [9]		15			tonne CO2-equiv./ track-km/year
	Single track support system [9]		2			tonne CO2-equiv./ track-km/year
	Track maintenance			2,9	2,0	tonne CO2-equiv./ track-km/year
	Station maintenance			108,7	0,8	tonne CO2-equiv./ track-km/year

Including capital wear.

According to the Schlaupitz estimate from Table 22, there is an emission of 3,3 tonnes of CO2-equivalents for each single track rail infrastructure km, including tunnels and bridges. The estimate for BART is very close. BART is part of San Francisco municipal transport system and has a large proportion of its tracks underground. Caltrain is mostly at ground level and its infrastructure has less GWP impact.

Many of BART stations are underground so the GWP-impact of station construction is greater for BART than for Caltrain. Construction of stations have a greater global warming impact in BART than construction of the railway itself. This is not the case for Caltrain. We also note that there is quite an impact from parking lot construction. The estimate for parking lots in the BART-system is at the same level as track base construction and track subbase construction from Schlaupitz.

The emission of greenhouse gases from rail infrastructure operation is estimated to be 14 tonnes pr track km pr year in Schlaupitz. The estimate for BART is greater, but it also includes parking lot lighting. The difference in electricity mixes in California and Norway will of course influence the estimate. Norway has almost exclusively hydro power as energy carrier for lighting. The emission in Norway comes from materials and machines used in operation of rail infrastructure. All in all, the operation estimate for Caltrain is close to the Norwegian estimate.

For maintenance of rail infrastructure, Schlaupitz gives an estimate of 17 tonnes pr track km pr year. His estimate do not include railway stations. For station maintenance alone, the BART railway system has an emission of greenhouse gases of 109 tonnes pr track km pr year. Track maintenance has lower emissions in BART and Caltrain than in Schlaupitz, this is probably due to more snow clearing, fences for wild animals etc for Norwegian railways than for the more urban railways around San Francisco.

Table 23 shows the emissions from road infrastructure construction, operation and maintenance. The estimates for tunnels and bridges are corrected for the proportion of tunnels and bridges pr road km. All in all, construction of one km two lane road in Norway leads to an emission of 959 tonnes of greenhouse gases [91]. This estimate includes tunnels and bridges. Construction of one km of rural road in USA leads to an emission of 365 tonnes of greenhouse gases [92] while the corresponding number for an urban road is 409 tonnes. As stated earlier, American roads have a support layer which is 30 cm smaller than in Europe and the layer of reinforcement materials is about 60 cm smaller. Also, the surface layer is 15 cm smaller. This, together with the fact that the estimate from Horvath and Chester does not include tunnels and bridges, goes a long way in explaining the difference in the estimates.

There is one other difference between the estimates. In the Schlaupitz estimate, almost 75% of all emissions come from substructure materials and construction. In the estimate from Horvath and Chester, the corresponding number is 14%. For surface layer, the picture of course is the other way round. The surface layer is probably replaced more often in USA since the surface layer is smaller. Aslo, traffic is heavier in USA than in Norway, and the lifetime used by Horvath and Chester is only a tenth of what Schlaupitz use for Norwegian roads.

[91] See Table 9-15, page 63. Loss of carbon sequestring is not included, only direct emissions included. Schlaupitz uses kg pr road-m which is translated into tonne pr road-km.

[92] Appendix B, Rural construction factors, page 124. The uathors use Mg/mi (with capital M) which is assumed to be Mega-gram pr mile. See http://no.wikipedia.org/wiki/Mg

Table 23 Emission of CO2-eqivalents from road infrastructure construction

Road Infrastructure tonne co2-eq. pr km				Schlaupitz	Horvath & Chester	
Construction	Road substructure	Two lanes *excluding* tunnels and bridges	Building	325		Metric tonne GGE/ km
		Two lanes, *only* tunnels and bridges	Building	51		Metric tonne GGE/km
		Four lanes *excluding* tunnels and bridges	Building	1 105		Metric tonne GGE/km
		Four lanes, *only* tunnels and bridges	Building	222		Metric tonne GGE/km
		Two lanes *excluding* tunnels and bridges	Materials	79		Metric tonne GGE/km
		Two lanes *only* tunnels and bridges	Materials	262		Metric tonne GGE/km
		Four lanes *excluding* tunnels and bridges	Materials	199		Metric tonne GGE/km
		Four lanes *only* tunnels and bridges	Materials	1195		Metric tonne GGE/km
		Manufacturing materials for rural local road USA			37	Metric tonne GGE/km
		Manufacturing materials for urban local road USA			46	Metric tonne GGE/km
		Process equipment rural road USA			2	Metric tonne GGE/km
		Process equipment urban road USA			2	Metric tonne GGE/km
		Transport materials for rural road USA			12	Metric tonne GGE/km
		Transport materials for urban road USA			14	Metric tonne GGE/km
	Road surface	Two lanes: Materials *excl.* bridges and tunnels		227		Metric tonne GGE/km
		Two lanes: Materials *only* bridges and tunnels		16		Metric tonne GGE/km
		Four lanes: Materials *excl.* bridges and tunnels		558		Metric tonne GGE/km
		Four lanes: Materials *only* bridges and tunnels		77		Metric tonne GGE/km
		Manufacturing materials for rural local road USA			111	Metric tonne GGE/km
		Manufacturing materials for urban local road USA			137	Metric tonne GGE/km
		Process equipment rural road USA			0,6	Metric tonne GGE/km
		Process equipment urban road USA			1,2	Metric tonne GGE/km
		Transport materials for rural road USA			204	Metric tonne GGE/km
		Transport materials for urban road USA			208	Metric tonne GGE/km
Operation		Two lanes standard road		11		Metric tonne GGE/ km/year
Maintenance	Standard	Two lanes		55		Metric tonne GGE/ km/year

The only estimates we have for road operation and maintenance come from Schlaupitz. He estimates an emission of 11 tonnes pr road km for operation and 55 tonnes pr road km for maintenance.

The discussion above has shown that the estimates from Schlaupitz are reasonable when compared to other available estimates. Based on his estimates we can construct Table 24 which shows emissions of greenhouse gases for different infrastructure activities. Numbers in Table 24 include both passenger and freight transport. Note that stations are *not* included in the infrastructure for railway. We include the amount of road km and km of single track railway in Norway as well as passenger transport work for the two infrastructures, measured in passenger kilometers. The weights included in the table are the same as used above. They measure the proportion of passenger transport work relative to total transport work (including freight) for each infrastructure. Passenger transport is converted to tonne-km by assuming each passenger weighs 86,5 kg [93].

Table 24 Emission of CO2-equivalents in tonne pr road km for different infrastructure activities for both passenger and freight transport

	Road	Rail
Construction (whole lifetime)	959	3 374
Operation (pr year)	11	14
Maintenance (pr year)	55	17
Lifetime	40	40
Km	93 247	4 114
Weight for passenger transport	0,24	0,67
Passenger km [94]	60 575	2910
Tonne-km	16 313	2 467

Based on this information we can estimate the emission of greenhouse gases in CO_2-equivalents for each passenger kilometer on each infrastructure. Table 25 shows the result. The total emissions of CO_2-equivalents from Table 24 are distributed on passenger and freight transport according to the weights in Table 24.

Table 25 Emission of CO2-equivalents pr passenger km for different infrastructure activities

CO2-equivalents in kg/passenger km	Road	Rail
Construction	0,009	0,080
Operation	0,004	0,013
Maintenance	0,020	0,016
Sum	0,033	0,109

From Table 25 we can conclude that road infrastructure has an emission of CO2-equivalents in the order of 0,0033 kg/pass-km or 33 g/passenger-km. The same figure for rail is 0,109 kg/passenger-km or 109 g/passenger-km. Thus, rail infrastructure has an emission pr passenger km which is about 76 grams higher for each passenger-km travelled.

[93] See http://www.ssb.no/emner/01/03/10/rapp_200849/rapp_200849.pdf , page 17
[94] For rail transport, passenger-km are calculated excluding passenger transport performed by tram and subway.

The construction of infrastructure produces emissions of CO_2-equivalents for rail which is almost 9 times the emission from road pr passenger-km. Operation is also more demanding for rail infrastructure, about 3 times more demanding. For maintenance, the relationship is the opposite, road maintenance produce emissions of CO_2-equivalents which is 1,25 times higher than for rail infrastructure.

The same table can also be constructed for freight transport. The total freight transport work for rail is 2 467 tonne-km in 2007 while the transport work for road was 16 313 millioner tonn-km. These numbers have been used to normalize the numbers in Table 26. Since freight transport is a much bigger part (76%) of total road transport than for total rail transport (33%), the figures for road infrastructure are much higher than the corresponding ones for rail. Maintenance is almost 27 times more demanding for road freight transport than for rail pr tonne-km, while construction acitivity is about 2,3 times higher pr tonne-km. Operation of infrastructure is about 6 times higher pr tonne-km for road infrastructure than for rail.

Table 26 Emissions of CO2-equivalents in kg pr tonne km for different infrastructure activities

	Road	Rail
Construction	0,104	0,046
Operation	0,048	0,008
Maintenance	0,239	0,009
Sum	0,391	0,063

Literature

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Appendix

Notes on railway infrastructure construction table

[1] Assuming single track. The estimate is without tunnels and bridges, but includes underground tracks and elevated or aerial tracks. BART (Bay Area Rapid Transit) has a multitude of different tracks.
[2] Numbers in primary energy.
[3] Numbers from Schlaupitz includes tunnels. (Note: Greater than corresponding number for total energy consumption for infrastructure!)
[4] Caltrain is diesel-driven
[5] Numbers from Schlaupitz weighted by proportion of meter tunnels and bridges pr track km
[6] Caltrain has much simpler stations,..." two platforms are constructed at grade on the side of the track" (Horvath and Chester, p 58). Numbers from Jonsson based on Swedish station number and track length.
[7] Assuming 25 years track lifetime, see Horvath and Chester, page 66
[8] Assuming 50 years track lifetime, see Jonsson, page 28
[9] Yearly contribution from material consumption for track substructure (Table 8-9, page 41) and support systems (Table 8-12, page 42). Energy impact from construction (not materials) in addition, see Table 8-3 and Table 8-12.
[10] Page 46, table 8-16
[11] Page 40, second paragraph.
[12] Heiberg, table 3-11, page 60.

Notes on road infrastructure construction table

[1] All numbers from Heiberg are in primary energy, numbers from Schlaupitz are in primary energy if not otherwise stated.
[2] Numbers for wearing layers and subbase layers obtained from PaLATE. Tunnels and bridges not included. http://www.ce.berkeley.edu/~horvath/palate.html referenced in Horvath and Chester, http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1015&context=its/future_urban_transport page 124.
[3] Excl. machines for maintenance, incl. replacement of surface layers, diesel for engines, road marking, filling materials.
[4] Including tunnels and bridges.
[5] Schlaupitz, table 9-14, including tunnel ventilation and signal systems.