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16. Abstract

This study examined interactions of environmental and safety measures for road transportation. The results showed that a vast majority of the examined measures support both policy objectives and thereby contribute effectively to sustainable transportation. However, there were also measures with conflicting effects, although the number of those measures was limited. In addition, there were a number of measures with no interaction. Furthermore, many potential effects were not documented and therefore in many instances only likely effects were noted.

There are two practical implications of this study. First, those measures that result in double benefits should be encouraged to be implemented. Second, in case of conflicting measures, the specific implementations should attempt to minimize the negative effects.

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Contents

Introduction

Road transportation has positive effects on the economy, but negative effects on safety and the environment. The magnitude of the road-safety problem worldwide has been recognized for decades (e.g., Peden, Scurfield, Sleet, Mohan, Hyder, Jarawan, and Mathers, 2004). Similarly, many environmental effects of road transportation have been discussed for a long time. However, the recent discussion of climate change has brought to the forefront the need to significantly curb greenhouse gas (GHG) emissions produced by road transportation.

Current transportation is predominantly based on the combustion of fossil fuels, making it one of the largest sources of air pollution and greenhouse gases (United Nations, 2010). Furthermore, transportation is the cause of other environmental effects, such as noise pollution and the loss of land and open space. However, the movement of goods and people is crucial for social and economic development; it enables trade and provides opportunities for employment, education, and leisure. Consequently, there is a need for sustainable mobility.

To meet the environmental and safety challenges of road transportation, a number of measures have been designed and implemented. This raises the issue of interactions between those two types of measures (e.g., Noland, 2009). Of specific interest are the impacts of current environmental measures on road safety, and the impacts of current road-safety measures on the environment.

This study was designed to examine potential interactions of environmental and safety measures for road transportation. A variety of potential interactions can occur. Some measures can be beneficial for both environmental and safety targets, some of them can conflict, or some may result in no interaction. It is important to identify measures that result in double benefits, because they represent effective sustainable-transportation measures. The identification of conflicting measures is important as well, because it would help assess the total benefits of a given measure.

Approach

This study reviewed road-safety effects of various measures targeting environmental problems of road transportation, and environmental effects of various road-safety measures. Three recent documents were used as the main sources for the selection of measures: *EPA Analysis of the Transportation Sector: Greenhouse Gas and Oil Reduction Scenarios* (EPA, 2010), *Greenhouse Gas Reduction Strategies in the Transport Sector: Preliminary Report* (OECD/ITF, 2008), and *The Handbook of Road Safety Measures* (Elvik, Høye, Vaa, and Sørensen, 2009). In addition to the selection of safety measures, the book by Elvik et al. (2009) provided a principal source for the selection of environmental effects of road-safety measures.

The study was limited to documented measures that have been used or will likely be used in the near future. The focus of the study was on road transportation. However, some measures dealing with modal split can influence other transportation modes as well. The magnitude of the effectiveness of the measures was not dealt with.

The covered environmental measures focused on air pollution and greenhouse gases. (Carbon dioxide is not considered an air pollutant, but a greenhouse gas because it contributes to global warming by preventing heat from escaping the earth's atmosphere.) However, other effects were discussed as well, such as noise, dust and dirt, barrier effect (for people or wildlife), pollution of vegetation, pollution of ground water, corrosion, disintegration of concrete structures, the space needed for road construction, intrusion into the landscape, use of nonrenewable resources, and light pollution.

The safety effects included measures designed to reduce the number of road crashes or the severity of injury given a crash.

Effects of environmental measures on road safety

Measures

EPA (2010) presented the following classification of the types of policies that could potentially be used to achieve environmental benefits for transportation: (1) vehicles, engines, and equipment, (2) fuels, (3) public funding for transportation infrastructure, (4) enhancements to current planning process, (5) information programs to address imperfect-information concerns, (6) taxes on carbon, fuel, vehicle distance traveled, and (7) cap and trade. These seven types of policies will be examined, along with the safety effects of controlling noise. The specific measures were adapted from EPA (2010) and OECD/ITF (2008).

Vehicles, engines, and equipment

The measures in this category include:

- Accelerated fleet turnover programs, such as "cash for clunkers"
- Programs that incentivize low-GHG purchases, such as feebates or tax incentives
- GHG standards
- R&D funding
- Manufacturer and start-up funding or tax incentives for production-facility retooling, or capital costs
- Requirements or incentives to retrofit existing fleets with low-GHG technologies (e.g., enhanced aerodynamics)
- Low-interest loans to fund capital investments in more efficient trucks and equipment
- Labeling of fuel consumption of new vehicles, to guide purchasing behavior towards more energy-efficient vehicles

Accelerated fleet-turnover programs are likely to result in safety benefits, because newer vehicles are safer. Specifically, the newer vehicles tend to be equipped with modern technology, such as electronic stability control (ESC), and the protection that a vehicle provides its occupants if involved in a crash has improved (Broughton, 2003; Folkhälsan, 2010). On the other hand, vehicle distance traveled tends to increase if the operating costs per distance are reduced (e.g., Greene, 1998). This effect somewhat reduces the positive safety effects. However, the specific safety effects have not been documented.

Many of these measures are likely to affect the average mass of cars (accelerated fleet-turnover programs, programs that incentivize low-GHG purchases, GHG standards, labeling of consumption of new vehicles sold). In general, it is well documented that the heavier the vehicle, the smaller the risk of injury for the people in that car, and the lighter the vehicle, the smaller the risk of injury for other road users (for a recent review, see Elvik et al., 2009).

The more challenging issue is whether the increased mass of vehicles improves the overall safety, including the fatality risk in one's own vehicle (internal risk) and the fatality risk in counterparts (external risk). Evans and Wasielewsky (1987) found that, if cars of similar mass crash into each other, the likelihood of driver injury (fatal or serious) increases with decreasing car mass (both for head-on crashes and for crashes in all directions). The results of Evans and Frick (1992) showed that, in comparison to a car weighing 830 kg, the fatality rate was higher for mass categories of 960-1,290 kg and lower for higher-mass categories (1,400-1,640 kg). This result suggests that mass reductions can be harmful for certain mass categories.

Elvik et al. (2009) presented a summary of studies that have attempted to measure the effects of car mass on both the risk of injury to people in the car and the risk of injury to the counterparts in multivehicle crashes. As expected, the risk to people in a car decreased with the increased weight of the car (approximately 50% lower risk in cars weighing more than 1,500 kg than for cars weighing less than 850 kg). However, the risk of cars injuring others increased the heavier the cars are. The external risk of the heaviest cars was found to be about 75% higher than the external risk of the lightest cars. Finally, the total number of injured persons was almost independent of car mass. These results suggest that the increase in the external risk with increasing weight might offset the gain in internal risk. Tolouei and Titheridge (2009) also pointed out that the distribution of mass within the fleet and other fleet characteristics are important factors in determining the relationship between mass and safety performance of vehicles.

Folkhälsan (2010) showed that the safety gap between large and small cars has decreased in terms of risk for fatality or permanent disability in crashes. Since 1980, the fatality rate has improved by 35% for small cars and by 25% for large cars. In addition, the difference in injury risk by vehicle weight in single-vehicle crashes is even smaller. Consequently, the difference between large and small cars has substantially diminished from the 1980s. Also, Chen and Ren (2009) showed that fuel-efficient vehicles can be as safe as, if not safer than, less fuel-efficient counterparts in accidents involving single-car crashes and side-impact collisions.

In summary, the above results are inconclusive. Specifically, some results support the conclusion that the large mass improves road safety, while others suggest that the total safety is relatively independent of the car mass. Furthermore, it is important to point out that the reviewed studies focused on multivehicle crashes, and crashes involving pedestrians have not been included.

Another broad area is the development of new types of vehicles because of programs that incentivize low-GHG purchases. Potential safety issues with electric vehicles have been discussed, such as crash damage to the new generation of batteries and what safety factors emergency services should take into account in crashes involving an electric vehicle (The Royal Academy of Engineering, 2010).

An emerging safety issue peculiar to electric and hybrid vehicles relates to whether they are too quiet to warn pedestrians (and especially visually impaired pedestrians) about the presence of the vehicle (Garay-Vega, Hastings, Pollard, Zuschlag, and Stearns, 2010; Refaat, 2010). Based on current knowledge, however, Sandberg, Goubert, and Mioduszewski (2010) concluded that there is no significant safety problem, because no study has shown any elevated pedestrian crash risk for quiet vehicles (e.g., current hybrid vehicles) and the current fleet of road transportation already includes vehicles that mask the quieter ones. Thus, the current results are inconclusive.

Other measures in this category have no documented effects on safety. In some cases, a measure has been shown to be safety-neutral as is the case for feebates (Greene, 2009), or a measure is too general to specify any safety effects (e.g., R&D funding).

Fuels

The measures in this category include:

- Increase of taxes on motor fuels
- Renewable fuels policies such as renewable-fuel standards and/or low-carbon-fuel standards
- Requirements to offset increases in GHGs from petroleum-based fuels (e.g., to address tar sands)
- Border tax adjustments for imports of higher-GHG fuels

An increase of taxes on motor fuels would likely result in a reduction in the amount of driving, due to either a reduction in the number of trips (e.g., by ridesharing (Jacobson and King, 2009)) or an increase in the use of public transportation. (For the effects of recent increased gasoline price on transit ridership, see Lane, 2010.) Consequently, there would be a reduction in exposure to crashes, which would have an overall positive effect on road safety. Another potential effect is that people are more likely to purchase vehicles that consume less fuel. Based on the comparison of countries with more and less fuel-efficient fleets, Noland (2005) showed that changes in vehicle fuel efficiency are not associated with changes in traffic fatalities. However, the specific effects of increased fuel taxes on road safety have not been documented.

Other measures in this category have no documented safety effects.

Public funding for transportation infrastructure

The measures in this category include:

- Funding for mass transit, compact urban development, traffic management (improved availability and quality, improved information, etc.)
- Infrastructure support for mode-shifting freight from truck to rail or barge
- Funding for development of the infrastructure needed to power electric or hydrogen vehicles

The first two measures are likely to have positive road-safety effects. First, the development of mass transit is likely to increase the use of public transportation over travel by car. This will improve road safety, because crash risk (per distance or per person-trip) is lower for public transportation in comparison with travel by car (ETSC, 2003; Beck, Dellinger and O'Neil, 2007). Second, infrastructure support for mode-shifting freight from truck to rail or barge is likely to result in lower vehicle exposure on roads, which would have positive safety effects (e.g., Elvik et al., 2009).

Funding for development of the infrastructure needed to power electric or hydrogen vehicles has no direct effects on road safety.

Enhancements to current planning processes (better integrated land-use, transportation, and environmental planning at the state and local level)

In general, it is reasonable to assume that many of these measures aim to reduce motor-vehicle distance traveled. For example, it is very well documented that the high density of residential areas results in lower traffic volume, which, overall, improves road safety. There are a number ways to affect travel by land use (for a review, see Victoria Transport Policy Institute, 2010). However, the road-safety effects of these measures are not documented (except if the main objective of the measure was to improve road safety) (Elvik et al., 2009).

A lack of documentation concerns other measures in this category as well. For example, environmental zones in which the maximum emissions level is limited (e.g., European LEZ, 2010) and parking policies do not have any documented road-safety effects to start with (Elvik et al., 2009).

Information programs to address imperfect-information concerns

The measures in this category include:

- Connecting broader shipper and carrier communities to maximize efficiency in system-wide operations
- Supporting ridesharing, car sharing, car pooling
- Supporting the use of public transport
- Supporting bicycling and walking
- Providing confidence in fuel savings from technologies and operational strategies
- Supporting reduction in idling

The first three measures are likely to have positive effects on road safety, because they aim to reduce total distance, which improves safety in general. In addition, the support of the use of public transport results in safety improvements through lower crash risks. Specifically (as indicated above), in comparison with cars, the risk of crashes (per distance or per person-trip) is lower for trains, buses, rapid transit, etc. (ETSC, 2003; Beck et al., 2007).

In contrast, the support of bicycling and walking reduces road safety, because the risk of crashes (per distance or per person-trip) is higher for unprotected road users (e.g., pedestrians, bicyclists) (ETSC, 2003; Beck et al., 2007). One could assume that, in areas where the number of bicyclists is high and drivers are used to taking them into account, as is the case in the Netherlands, the crash risk of bicyclists could be lower if there were a high-standard infrastructure for bicycle use. However, the crash rate of bicyclists is higher than that of car occupants also in the Netherlands (SWOV, 2009b).

The safety effects of other measures are unknown. For example, the effects of ecodriving training on safety have not been widely examined, and no specific results are available (Haworth and Symmons, 2001).

Taxes on carbon, fuel, and vehicle distance traveled

All these taxes are likely to reduce the total distance driven and thereby improve safety. In addition, congestion pricing was included in this category. The measure is usually designed to change the travel behavior so that car driving will decrease and walking, cycling, and the use of public transportation will increase. The results from Stockholm and London show that the number of injury crashes have declined as a result of congestion pricing (City of Stockholm, 2006; Transport for London, 2006).

Cap-and-Trade

There are no specific or direct effects on road safety.

Controlling traffic noise

There are four general options for controlling traffic noise (Trafficnoise, 2010): constructing a barrier wall, increasing the isolation of the home, masking the noise, or controlling the noise at the source. (The last option focuses on factors such as engine, intake air, exhaust, cooling fan, transmission or driveline, and tire-pavement interaction (Herman, 1998).) These measures have no documented effects on road safety.

Effects of road-safety measures on the environment

The second edition of *the Handbook of Road Safety Measures* (Elvik et al., 2009) provides summaries of more than 2,000 evaluation studies regarding the effects of 128 road-safety measures. In addition to safety effects, the authors briefly describe effects on the environment. Overall, 107 of those 128 road-safety measures do not have any significant effects on the environment, or the effects have not been documented, and four do not primarily focus on safety. Consequently, the following analysis included the following 17 safety measures that have effects on the environment that have been documented or are otherwise evident:

- Bypasses
- Urban arterial roads
- Roundabouts
- Grade-separated junctions
- Road lighting
- Resurfacing of roads
- Winter maintenance of roads
- Area-wide traffic calming
- Environmental streets
- Pedestrian streets
- Speed limits
- Regulating automobile engine capacity (motor power) and top speed
- Studded tires
- Daytime running lights for cars
- Periodic motor vehicle inspections
- Land use plans (urban and regional planning)
- Changes in the modal split of travel

Given the large number of excluded measures, it is acknowledged that some of those measures might have environmental effects as well. However, it is assumed that the following discussion will reveal the main environmental effects of safety measures overall.

Bypasses

Although environmental effects of a bypass are frequently evaluated before implementation (e.g., Haussler and Rekenthaler, 1999), only one study was found to report those effects after implementation. Specifically, Elias and Shiftan (2007) showed that the implementation of five bypasses in Israel had major effects on land-use development in the cities.

The main objective of the implementation of bypasses is to remove traffic from one site to another, typically farther away from city centers. This implies that any evaluation should cover the environmental effects at both sites. It is reasonable to assume that many negative effects are reduced at the original site (e.g., noise, air pollution) if the traffic volume and congestion are reduced. At the same time, those problems might be increased at sites with increased traffic. Consequently, the total effects of the bypasses are challenging to predict.

Urban arterial roads

As is the case with bypasses, new urban arterial roads are designed to remove traffic from the existing road network to new routes. The number of evaluations focusing on the environmental effects of implemented urban arterial roads is limited. However, the available evaluations show that arterial roads can result in positive environmental effects, such as the reduction of noise and air pollution (Clench-Aas et al., 2000; Klæboe et al., 2000). On the other hand, increasing road capacity is likely to induce new traffic in the long run (Elvik et al., 2009).

Roundabouts

There are potential beneficial effects on air quality when intersections are replaced by roundabouts. However, air-quality benefits depend on many factors, such as traffic volume, number of roads entering the roundabout, and the type of intersection the roundabout replaces. Overall, the environmental effects seem positive if a signalized intersection is replaced by a roundabout.

Bendtsen (1992, cited in Elvik et al., 2009) found that emissions of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxide (NOx) (calculated in grams per kilometer driven per car) are approximately 5-10% lower at roundabouts than at signalized intersections.

Várhelyi (2002) studied intersections on arterials that were rebuilt as small roundabouts. One of the intersections was originally signalized while others were yield-regulated. Before and after the roundabouts were installed, random cars were selected and followed with an instrumented vehicle that aimed to imitate that car's driving pattern. The results showed that, at the roundabout that replaced the signalized junction, CO emissions decreased by 29%, NOx emissions by 21%, and fuel consumption by 28%. At roundabouts replacing yield-regulated junctions, CO emissions increased by 4%, NOx emissions by 6%, and fuel consumption by 3%.

Züger and Porchet (2001) conducted a somewhat similar study, but without following any particular car. Where a signalized intersection was replaced by a roundabout, crossing times, fuel consumption, and emissions of pollutants were reduced. However, the effects on fuel consumption and emissions were frequently the opposite at the non-signalized intersections. The effects depended very much on local factors such as the amount of traffic, frequency of interruption of traffic flow by pedestrians, the ratio of traffic density on the different branches, etc.

Grade-separated junctions

Elvik et al. (2009) found no studies that show effects of grade-separated junctions on environmental conditions. However, the authors indicate that grade-separated interchanges require more space than at-grade intersections. Ramps and bridges can appear dominant in the landscape and spoil the view for people living along the road. Because of more constant speed, fuel consumption may be reduced.

Road lighting

Elvik et al. (2009) found no studies on the effects of road lighting on noise or pollution. However, road lighting consumes electricity. Environmental effects of power consumption will depend on how the energy is produced.

Shaflik (1997) points out that energy wasted by the misdirection of roadway light can be considered wasted energy. It has been estimated that up to 30% of all roadway lighting is lost or misdirected from the intended source. The International Dark-Sky Association has assessed this energy loss in the United States at over $1 billion per year and has noted the corresponding increases in air pollution resulting from this wasted energy (Shaflik, 1997).

Resurfacing of roads

Road surface types can affect noise in the vicinity. For example, Dravitzki, Walton, and Wood (2006) found a 6 dBA difference between road-surface types, which equates to 40% of the noise difference between a high-noise area and a low-noise area. In addition, the dust problem of dry gravel roads is eliminated if the road is paved (Elvik et al., 2009). However, no studies were found of the effects of paving gravel roads on the environment.

Winter maintenance of roads

The most important winter-maintenance measures are snow clearance, sanding, and salting. Winter-maintenance measures, especially salting, can have significant effects on the environment.

The effects of salting depend on a wide range of factors unique to each site (TRB, 1991). The effects most frequently cited in the literature are damage to roadside vegetation (trees, shrubs, ground cover, grasses, wetland vegetation), water (surface water, ground water, rivers and streams, lakes and ponds, aquatic life), soil, wear and tear on roads, and corrosion of bridges and vehicles.

In addition to salting, road dust has been recognized as a dominant source of fine particulates (PM10), especially during spring in sub-arctic urban areas (Kupiainen, 2007).

The high proportion of road dust in sub-arctic regions of the world has been linked to the snowy winter conditions that make it necessary to use traction-control methods. Several of these methods enhance the formation of mineral particles from pavement wear and/or from traction sand that accumulate in the road environment during winter. When snow and ice melt and surfaces dry out, traffic-induced turbulence makes some of the particles airborne.

Area-wide traffic calming

Area-wide traffic calming is the coordinated use of traffic-control measures in a relatively large, defined area (Elvik et al., 2009). These areas are predominantly residential and are frequently located close to the central commercial sector of a city (Bunn, Collier, Frost, Ker, Steinbach, Roberts, and Wentz, 2009). Measures include improving main roads, road closures, changes to intersections, changes to the road environment (e.g., speed bumps and traffic circles), improvement in pedestrian-crossing facilities, and the implementation of roundabouts (Bunn et al., 2009; Elvik et al., 2009). A recent review by Ahn and Rakha (2009) showed that, while there are some studies indicating air quality benefits due to traffic calming, several studies have concluded that they increase vehicle fuel consumption and emissions.

Area-wide traffic calming can reduce noise if traffic volumes on residential streets are reduced and traffic is directed to other roads (Øvstedal, 1996, cited by Elvik, 2009).

Environmental streets and pedestrian streets

While driving is prohibited on pedestrian streets (except for delivery at specific times of the day), environmental streets are roads where through traffic is permitted, but where the road characteristics are designed for low speed and a high degree of alertness. A review of Scandinavian studies (Elvik et al., 2009) showed noise- and air-pollution improvements after the implementation of pedestrian streets. On the other hand, the implementation of environmental streets has not resulted in conclusive results. Furthermore, the environmental effects (e.g., noise) of environmental streets and pedestrian streets on surrounding streets were negative.

Speed limits

In general, pollutant emissions depend on speed levels. For light gasoline vehicles, CO and CO_2 emissions typically are high at low speeds and decrease up to 60-80 km/h and then increase again (André and Hammarström, 2000). The same pattern can be found in a wide range of vehicles in the overall on-road fleet. In addition to the mean speed, emissions depend on whether the vehicle is accelerating, cruising, or decelerating (LeBlanc, Sivak, and Bogard, 2010). Consequently, the studies on the effect of speed limits on the environment have focused on freeway (motorway) driving.

After the introduction of a limit of 100 km/h instead of 120 km/h on particular sections of Dutch motorways, driving speed reduced sharply, resulting in lower fuel consumption and lower NO_x, CO, CO_2, and hydrocarbon emissions (den Tonkelaar, 1991). However, speeds slowly increased again, with the result that benefits largely disappeared.

Van Beek, Derricks, Wilbers, Morsink, Wismans and van Beek (2007) evaluated the effects of reducing the speed limit from 100 km/h to 80 km/h on another Dutch motorway. The study showed a decrease of 4-6% in NO_2 concentrations. The reduction in NO_x was about 13% and the reduction in PM_{10} was 1%.

Baldasano, Gonçalves, Soret, and Jiménez-Guerrero (2010) assessed the effect of reducing the speed limit from 120 or 100 to 80 km/h on urban air quality on motorways in Barcelona. Overall, the speed limits reduced emissions by 5-8% (depending on the area studied).

There are two main sources of traffic noise (Ward, Robertson and Allsop, 1998): vehicle engines and the interaction between tires and road. The tire-road noise increases substantially with speed, and it dominates the total noise at higher speeds (i.e., above 20-40 km/h for new cars and above 30-60 km/h for new trucks). Consequently, the speed limits (which usually result in lower speeds) are likely to lead to lower levels of vehicle noise.

Studded tires

Although the environmental effects of studded tires vary by traffic concentration (proportion of light vehicles versus heavy vehicles), speed, pavement (bare versus icy/snowy), stud type, etc., it is well documented that the use of studded tires increases asphalt wear, particle pollution, and noise (for review, see Elvik et al. 2009; Gustafsson, 2006).

Daytime running lights for cars

The use of daytime running lights (DRLs) increases fuel consumption which, in turn, increases emissions (e.g., SWOV, 2009a). However, DRL power consumption is affected by the actual DRL implementation. There is a large difference between using full-power low beams and dedicated lamps (and especially so if the light sources for the dedicated lamps are LEDs). In addition, automatic switches can be used to turn off unnecessary lighting (e.g., rear lamps) when DRLs are energized.

Regulating automobile engine capacity (motor power) and top speed

This measure includes two types of power/speed limiters. First, there are governors that limit the overall maximum speed. These types of limiters are applied in Europe for trucks and buses. Second, there have been several studies investigating the safety effects of intelligent speed adaptation (ISA), which is an in-car technology that warns the driver about speeding, discourages the driver from speeding, or prevents the driver from exceeding the speed limit.

Overall, as discussed above, cars at high speeds use more fuel than cars at intermediate speeds and thus cause more exhaust emission. Carslawa, Goodman, Lai, and Carsten, (2010) found for motorway-type roads an average savings in CO2 of about 6% when mandatory speed control was used, compared with baseline conditions. For most other types of roads, speed control had very little effect on emissions of CO2, and in some cases can result in increased emissions for urban roads with low speed limits.

Periodic motor vehicle inspections

Based on their review, Rompe and Seul (1985) concluded that periodic inspections can reduce CO emissions by 20% and HC emissions by 10%. However, modern engine technology might have reduced these effects.

Land use plans (urban and regional planning)

Urban planning integrates land-use planning and transportation planning to improve built-up, economic, and social environments of communities. Regional planning focuses on larger-scale environments (and at a less detailed level). Because the severity of environmental problems caused by road traffic is strongly related to traffic volume (Elvik et al., 2009), a land-use pattern inducing more traffic will generally increase environmental problems (noise and pollution). For example, Lindsey, Schofer, Durango-Cohen, and Gray (2011), using data from Chicago, found that decreased residential density increased vehicle distance traveled, energy consumption, and CO_2 emissions. Similar effects of land use on travel patterns have been shown recently in other countries as well (e.g., Dieleman, Dijst, and Burghouwt, 2002; Pan, Qing and Zhang, 2009; Lin and Yang, 2010).

Changes in the modal split of travel

The specific road-safety measures included by Elvik et al. (2009) that affect the modal split were (1) changes in the supply of public transport, (2) changing the main mode of transport for journeys of a given length, (3) the crash rate on roads and streets with and without public transport, and (4) measures that can affect the demand for public transport. From an environmental point of view, the following discussion focuses on the air-quality effects of cars and public transportation.

Table 1 shows average selected emissions, CO_2, and energy consumption by vehicle type retrieved from a current Finnish database. The Australian data for energy consumption per person kilometer by mode show a similar pattern (Australian Government, 2009).

Table 1
Selected emissions, CO2, and energy consumption per person kilometer (pkm) by vehicle type (Lipasto, 2010). Data for cars are from 2010, for buses from 2009, and for trains from 2007.

Environment	Vehicle, fuel type (average number of occupants)	CO [g/pkm]	HC [g/pkm]	NOx [g/pkm]	PM [g/pkm]	CO2 [g/pkm]	Fuel consumption [MJ/pkm]
Rural (highway/ intercity train)	Car, gasoline (1.9)	1.00	0.069	0.21	0.002	91	1.2
	Car, diesel (1.9)	0.04	0.012	0.30	0.019	85	1.2
	Bus, diesel (12)	0.05	0.022	0.42	0.010	51	0.7
	Train, electricity	0.01	0.001	0.02	0.003	15	0.4
Urban	Car, gasoline (1.3)	1.70	0.190	0.22	0.002	151	2.1
	Car, diesel (1.3)	0.18	0.360	0.42	0.029	153	2.1
	Bus, diesel (18)	0.07	0.011	0.61	0.013	62	0.8
	Train, electricity	0.01	0.002	0.03	0.004	22	0.7

The data in Table 1 show that train transportation is most efficient overall, followed by bus transportation, and then cars. However, the efficiency of all modes can be increased from what is shown in Table 1. Particularly, the rate of public transportation can be much higher in countries with higher population density than in Finland. For example, Khanna, Jain, Sharma, and Mishra (2011) suggested that in Delhi, mass transit modes can lead to a considerable decline in energy demand. The rail-based systems are expected to achieve a much greater reduction than bus-based systems. Finally, Table 1 shows that there are substantial differences between rural and urban environments, with higher emissions, CO2, and fuel consumption in urban areas.

The results given in Table 1 represent operational emissions and fuel consumption. Based on U.S. data, Chester and Horwath (2009) calculated the life-cycle energy use and emissions (including nonoperational and infrastructure components) by vehicle type. The results showed, for example, that total life-cycle energy inputs and GHG emissions contribute an additional 63% for road and 155% for urban rail systems over vehicle operation. Nevertheless, the overall results were comparable to those in Table 1 (with similar order of modes).

Summary of the analyses

Tables 2 and 3 summarize the analyses presented above. Specifically, Table 2 classifies the environmental measures by their effects on road safety. The categories include positive and negative effects by the strength of the evidence (documented or likely). Table 3 presents the environmental effects of the safety measures in a corresponding manner.

Table 2
Safety effects of environmental measures.

Safety effects			
Negative		Positive	
Documented	Likely	Likely	Documented
	Support bicycling and walking	Accelerated fleet turnover programs Increase of taxes on motor fuels Funding for mass transit, compact development, and traffic management Infrastructure support for mode-shifting freight from truck to rail or barge Better integrated land use Connect broader shipper and carrier community to maximize efficiency in system-wide operations Support ridesharing, car sharing, and car pooling Support the use of public transport Taxes on carbon, fuel, and vehicle distance traveled	Congestion pricing

Table 3
Environmental effects of safety measures.

Environmental effects			
Negative		Positive	
Documented	Likely	Likely	Documented
Winter maintenance of roads Studded tires Daytime running lights for cars	Road lighting Grade-separated junctions	Bypasses Grade-separated junctions Resurfacing of roads Pedestrian streets Environmental streets	Urban arterial roads Roundabouts Resurfacing of roads Area-wide traffic calming Speed limits Regulating automobile engine capacity (motor power) and top speed Periodic motor vehicle inspections Land use Changes in the modal split of travel

Tables 2 and 3 show that the majority of interactions are positive. However, many identified interactions have not been documented, and therefore in many instances only likely effects were identified. This was the case especially for safety effects of environmental measures.

Discussion

This study examined interactions of environmental and safety measures for road transportation. Based on recent documents that classified those measures, the safety effects of environmental measures and the environmental effects of road-safety measures were identified.

The main results showed that a vast majority of the examined measures support both policy objectives and thereby contribute effectively to sustainable transportation. However, there were also measures with conflicting effects, although the number of those measures was limited. Specifically, no examined environmental measure had documented negative effects on road safety, but an increase in bicycling and walking is likely to have negative effects on road safety. The road-safety measures with documented negative effects on the environment included winter maintenance of roads, studded tires, and daytime running lights. Road lighting and grade-separated junctions are likely to have negative effects on the environment. In addition, there were a number of measures with no interaction.

Furthermore, the results showed that many potential effects were not documented and therefore in many instances only likely effects were noted. This result implies that further research is needed to verify the interactions of many measures. It is also recommended that the scope of this type of analysis be expanded to cover interactions other than those between the environmental and safety effects (including other health-related aspects, mobility, and equity).

There are several limitations of this study that should be taken into account in applying the results. First, the ranges of specific implementation of each potential measures are too large to allow for discussion of each implementation, and therefore the study focused only on relatively broad environmental and road-safety measures identified by earlier research. However, it is assumed that the selection of the examined measures covered the most important measures. Second, the classification of road-safety and environmental effects was broad, and only main effects were included. Several measures can have positive and negative effects, and the final outcome of any measure always depends on a particular implementation. Third, this study did not attempt to quantify the effectiveness of the examined measures. Consequently, it could be that a measure supports both environmental and safety targets, but the effectiveness of that measure is low in relation to environment, safety, or both.

There are two practical implications of this study. First, those measures that result in double benefits should be encouraged to be implemented. Second, in case of conflicting measures, the specific implementations should attempt to minimize the negative effects.

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