Resources, Conservation and Recycling
33 (2001) 235–265

resources, conservation and recycling

www.elsevier.com/locate/resconrec

Trade and recycling of used tyres in Western and Eastern Europe

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Received 19 October 2000; accepted 6 June 2001

Abstract

Truck tyres can cause significant environmental pressure through the life cycle. The main aim of this paper is investigate to what extent international policy measures on foreign trade, international recycling and harmonisation of legislation can contribute in effectively reducing environmental pressure caused in the truck tyre life cycle. A two-region simulation model, representing Western and Eastern Europe, is developed that integrates the complete life cycle, incorporates environmental impacts in its economic analysis, is technically dynamic by accounting for learning-by-doing effects, and allows for variations in trade of new and old truck tyres. In this study the economic, environmental and social effectiveness of harmonisation and trade measures in the European life cycle for truck tyre is tested. Several conclusions can be drawn from the model simulations. First, the environmental effects caused by the trade of used tyres from Western to Eastern Europe are of limited impact on the overall environmental damage caused by truck tyres. The consumption stage is by far the main contributor to environmental damage. Within the marginal analysis of trade, harmonisation of disposal fees illustrated to generate very limited positive results. The private and external costs in the solid waste management (SWM) stage are too limited to have a notable impact on the overall configuration of the European tyre life cycle. The introduction of strict laws on tread depth in Eastern Europe has a much stronger impact on material flows than the harmonisation scenario. This suggests that domestic policy measures should be the primarily focus on interventions in this stage of the life cycle, for instance, by improving the management of tyre pressure. Because trade of used tyres has little impact on the consumption stage, this issue should not get priority in European environmental programs.

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PII: S0921-3449(01)00082-9

Keywords: International trade; Recycling; Environmental policy; Tyres; Europe

1. Introduction

By facilitating the secure transport of materials, goods and passengers tyres can be considered an asset for society. Nevertheless, tyres can cause environmental pressure in many ways, in different stages of the life cycle of tyres, including production, consumption, and solid waste management (SWM). The production stage is important because the tyre industry is the world's largest consumer of natural and synthetic rubber. The consumption stage is important because the maintenance of tyres has a significant impact on the environmental performance of tyres (Nicoletti and Notarnicola, 1999). Due to the increased number of vehicles, the 'mountain' of used tyres has grown dramatically during the last decades. Every year, approximately 800 million scrap tyres are disposed around the globe. This amount is expected to increase by approximately 2% each year (UNCTAD, 1996; EEA, 1995).

In analysing environmental impacts of the life cycle of tyres, solutions can be found at the local and the international level. At the local level, the main issue is in which stage of the life cycle the most efficient environmental gains can be achieved. This question has been extensively addressed in Van Beukering and Janssen (2000). Results indicate that, among other things, the greater part of the overall environmental impact during the life of a tyre occurs before disposal. This result implies that emphasis in environmental policies related to tyres should shift from the waste stage to the consumption stage.

At the international level, the main question is to what extent international policy measures on foreign trade, international recycling and harmonisation of legislation can contribute in effectively reducing environmental pressure caused in the tyre life cycle. This question on the importance of international policies in the life cycle of tyres is the main aim of this paper. Various international scenarios are simulated, using the Western and Eastern European life cycle of truck tyres as a case study. The international dimension of the scenarios implies that either variation in trade is simulated or that standards on safety and waste disposal are harmonised at the European level. These scenarios are inspired by policy development in the European Union. A two-region simulation model is developed that is dynamic in nature, integrates the complete life cycle, incorporates environmental impacts in its economic analysis, accounts for learning-by-doing effects, and allows for variations in trade of new and old truck tyres.

The paper is structured as follows. To explain the context of truck tyre life cycle, a qualitative description of the tyre cycle in Europe is provided in Section 2. In this section policies and other issues are also discussed. In Section 3, a dynamic systems model is introduced for the analysis of the truck tyre life cycle. The results of various scenarios are presented in Section 4. In Section 5 conclusions and recommendations are formulated.

2. Trends and issues

The tyre life cycle traditionally comprises five main stages (Nicoletti and Notarnicola, 1999). These include extraction, production, consumption, collection of used tyres and waste management. A simplified version of the tyre cycle for one region is depicted in Fig. 1. As explained in the coming section, the configuration of the life cycle in each country depends on local economic and institution conditions.

2.1. Extraction and production

In the extraction stage, the generation of the basic components of a tyre takes place. The components consist of synthetic and natural rubber, textile, steel and chemical additives. The proportion in which these components are used depends on the specific characteristics of the tyre. This is demonstrated by looking at the ratio between natural and synthetic tyres: generally, truck tyres have a larger natural rubber content than passenger cars. An alternative component for rubber is ‘reclaim’ which is the material recovered from used rubber products. Because its physical properties are not as good as new rubbers (i.e. elasticity, flexion, and chemical resistance), however, the proportion of reclaim in tyre applications is limited to 10% (Guelorget et al., 1993).

To understand the manufacturing stage, one should be aware of the composition of the tyre. The tyre roughly consists of the casting or carcass that forms the skeleton of the tyre and the tread that consist mainly of rubber and therefore in most cases can be renewed (e.g. retreading). As shown in Fig. 1, the tyre can be produced in three ways: as new tyres, as retreaded tyres and as re-used tyres.

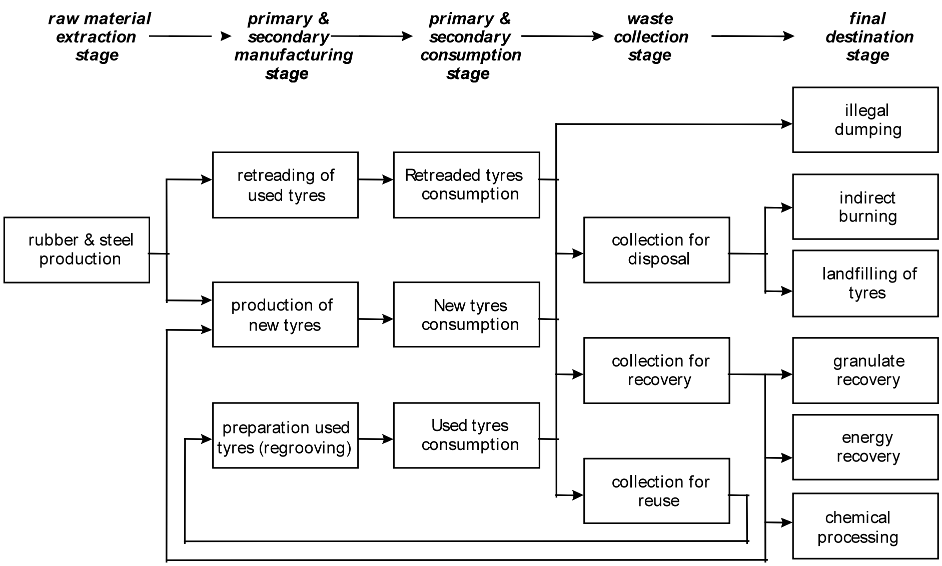

Fig. 1. The lifecycle of a tyre.

The manufacturing of a new tyre is a complicated process requiring a high level of technology. Therefore the scale of operation in Western and Eastern Europe is also relatively large, exceeding 50 000 tonnes per year. Labour costs account for 30% of the total costs (EPA, 1995). Manufacturing new tyres is the most environmentally intensive method of production. Energy consumption, for example, is 15 times higher than for retreading (Rosendorfová et al., 1998). On the other hand, due to the large scale of operation, plants are generally equipped with comprehensive pollution abatement measures.

Retreading involves stripping the old tread from a worn tyre and reclothing the old casting with a tread made from new materials. Retreading brings environmental benefits, as it extends the tyre life span. It saves 80% of raw material and energy necessary for production of a new tyre and reduces the quantity of waste to be disposed. The price of retreaded tyres is between 30 and 50% lower than the price of a new tyre. Nevertheless, they deliver the same mileage as new tyres (Ferrer, 1997; ETRA, 1996). Despite these economic and environmental advantages retreading in some European countries is still lacking. Difficulty in supply of retreadable casings, competition with cheap non-retreadable tyres and poor reputation of retreads' quality are some of the barriers to wider use of retreads. The main negative environmental impact of retreading is the health damage to workers resulting from volatile organic compound (VOC) emissions.

Reuse of tyres is not a real manufacturing option. Nevertheless, this process does result in usable tyres. The reuse of partly worn tyres may involve regrooving by which a new pattern is grooved into the tread base that remains after the pattern has been worn away by use. This technique is carried out primarily on truck tyres since these are designed with sufficient tread thickness. If the process is carried out correctly, approximately 30% extra mileage will be obtained for only 2.5% of the cost of a new tyre. Retreaders oppose direct reuse and regrooving since it makes further retreading more difficult, more expensive and in most cases even unfeasible. Depending on the remaining tread depth, disposed tyres are also reused directly. In many countries, the official standards, which is 1.6 mm for the European Union, are violated. Tyres that have been replaced before the minimum tread depth is reached generally enter international trade for direct reuse. From an environmental perspective, direct reuse and regrooving prolongs life span of a tyre. The increased imports of reusable tyres, however, may also increase the waste burden due to the short life span of reusable tyres. Moreover, increased risks for accidents may result from driving on worn-out tyres.

2.2. Consumption

Driving behaviour and neglecting the tyre pressure are the main factors influencing environmental performance in the consumption stage of tyres. Improvements in the tyre manufacturing over the past 40 years have more than doubled the mileage of tyres, yet this technical limit is rarely met. Quick acceleration, not observing speed limits, abrupt braking and not taking into account the state of road surface are all forms of driver behaviour that cause the original tread to dwindle at a great rate. Currently, steel belted radial passenger tyres last approximately 65 000 km. If these tyres are properly inflated, rotated, and otherwise cared for, a lifetime of 95 000–128 000 km may be achieved. A tyre loses up to 10% of its weight until it is disposed of. Most of the dissipated material comes from the tread, which is made of rubber only. If the casing is in a good state once the tread is finished, tyres can generally be retreaded. Retreads historically have a poor public image. Most retreaders, however, claim that there is no quality difference between new tyres and retreads (Environment Agency, 1998).

Driving behaviour and neglecting pressure also has a major impact on energy consumption. The fuel used to overcome the rolling resistance of the car tyre accounts for 15% of the total fuel consumption. If tyre pressure is not monitored this share may increase too more than 20%. A test in the UK proved that only 22% of the cars and trucks drive with the correct tyre pressure. The majority of the drivers under-inflate their tyres by 10–15% (Environment Agency, 1998). Another issue in the consumption stage is the introduction of energy-efficient tyres (i.e. eco-tyres, smart tyres). These can save up to 6% of a vehicle's fuel.

2.3. Waste collection and management

The collection of tyres is considered a separate stage in the life cycle. Used tyres are accumulated after replacement by a new one or when scrapping a vehicle. Various parties are involved. Generally, tyres are collected in tyre service centres. Consumers pay a limited fee to the service centre for proper disposal of the used tyre. For example, in the Netherlands, consumers pay approximately €2 per tyre (€300 per metric ton) for disposal. The service centre passes roughly 50% on to the broker. In turn, the service centre passes part of that fee on to brokers who separate out the reusable and retreadable tyres. The broker may export the tyre either for reuse or retreading. Part is marketed to domestic retreaders or other recovering agents, such as cement kilns.

The final destination stage describes the ultimate location where used tyres arrive. The term 'used tyre' defines a tyre at the end of its first life cycle. Two sub-types of used tyres are distinguished. The 'partly worn tyre' is a used tyre that can either directly be reused or retreaded. The 'worn out' or 'scrap tyre' is a used tyre that cannot be reused for its original purpose but may have a further use as a material or energy. As shown in Table 1 the configuration of processing options varies widely within Europe.

Worn-out tyres are generally used for material recovery or recycling. The options to recover material include mechanical grinding, cryogenic grinding, reclaiming and pyrolysis. In mechanical grinding, scrap tyres and tyre related rubber waste are reduced into various particle sizes. After grinding the material, steel and textile are removed. In the cryogenic grinding process the whole tyres are cooled down to the below the glass transition temperature, using liquid nitrogen. The cooled rubber is reduced to a very fine powder. The process enables rapid separation of textile, steel and rubber. In view of its environmental performance, grinding is an energy intensive process and has relatively high dust emissions. The economic and environ-

Table 1
Processing options of used tyres in Europe (1996)

Country	Volume (metric tons)	Percentage of total volume processed by individual options					
		Retreading	Physical application	Material recovery	Energy recovery	Landfill	Net-export
Belgium	70 000	11	8	14	25	42	n.a.
Czech Rep.	60 000	27	5	8	25	35	n.a.
Denmark[a]	19 000	26	8	14	9	49	0.5
France	375 000	20	7	7	15	47	4
Germany	600 000	20	n.a.	14	45	21	n.a.
Italy	260 000	22	n.a.	15	23	40	n.a.
Netherlands	65 000	37	n.a.	8	32	0	23
Norway	33 000	4	n.a.	n.a.	42	44	10
Spain	139 000	25	8	9	1	58	n.a.
Sweden	60 000	5	7	12	64	5	7
UK	370 000	31	5	11	27	26	n.a.

[a] Includes only tyres for motorcycles, cars and vans; n.a. = data not available. Source: Rosendorfová et al. (1998).

mental advantage of grinding is that it generates recyclable rubber and useful by-products such as steel and textile, which also can be recycled. The most common application of granulate is in rubberised asphalt. Although this seems to be a promising outlet for recycled rubber, because of its relatively high cost this application is not widespread in Europe.

Chemical processing of size-reduced tyres, such as pyrolysis, produces rubber reclaim. The resulting compound is submitted to a further thermo-mechanical or high-pressure steam process where additives are incorporated depending on the final product requirements. The final product is reclaim. Reclaim can be used in high value commercial applications requiring high performing rubber such as tyres, bicycle tyres, automotive moulded parts, soles and heels, etc. Compounds reclaim is almost half the price of virgin rubber. Using rubber reclaim can be even more profitable for the tyre industry, especially when production waste is recycled and reused within the factory where it is generated. This might result in additional revenues from eliminating disposal fees and transportation cost. Over the last few years the reclaim industry has declined. The main causes have been substitution of raw rubber by other materials, decrease in prices of materials and increased quality requirements for rubber articles.

The high energy content of tyres initiated several applications of post-consumed tyres for energy recovery. For example, many worn out tyres are used as a supplemental fuel in cement kilns. In Europe, USA, Japan and Korea, cement kilns belong to most common end users of energy content of tyres. In some countries, such as Austria, France, Germany and Sweden up to 65% of the total used tyre is incinerated in cement kilns. These high shares are partly due to the emphasis on technological developments achieved in tyre derived fuels. Alternatively, totally dedicated tyres-to-energy power plants are built in Europe. A major advantage of using worn out tyres in cement kilns is that it does not generate solid waste and substantial sulfur emissions because the ash residues from the tyre combustion are bound to the final product (Jones, 1997).

Traditionally, landfilling is the most common method for disposal. Tyres can be disposed in landfills and in monofills. In landfills scrap tyres occupy a large space and remain intact for decades posing increased environmental and public health risks related to possible leakage and danger of uncontrolled burning. When whole tyres are buried in a landfill they trap air and have tendency to migrate to the top of a closed landfill breaking the sanitary landfill cap and causing costly damages to the landfill cover. Whole tyres easily trap rainwater and therefore create a favourable environment for insects such mosquitoes that increase the risk for malaria (EPA, 1995). The European Commission recently accepted directive that bans the disposal of whole tyres to landfill by 2003 and shredded tyres by 2006 (European Commission, 1997).

A scrap tyre monofill is a landfill that stores tyres only. Monofills are more desirable than landfills as they facilitate material and energy recovery in the future. After the European ban on landfills is operational, monofills form a temporary solution in those European countries where capacities for processing used tyres are limited. The potential advantage of such monofills is that they can be reconsidered as future used tyre collection sites and distribution centres. However, monofills also form a serious source of fire outbreaks. These fires may cause significant atmospheric and surface water pollution (Lemieux and Ryan, 1993; Steer et al., 1995).

A growing problem in the waste management stage is the increasing incidents of illegal dumping of old tyres. Generally these tyres have already been sorted: only the tyres that are no longer retreadable or reusable are fly-tipped. Related to this problem is the abandoned monofill sites without processing the stored tyres. Such examples have been recorded in Canada, USA, the Netherlands and the UK (Environment Agency, 1997; EPA, 1995). The introduction of landfill taxes and collection fees are closely linked to this phenomenon. Collectors accumulate used tyres from car repair shops, receive the collection fee, sort out the useful tyres and dump the remaining. Illegal dumping of tyres mainly causes significant aesthetic pollution.

2.4. Trade of old and new tyres

Throughout the life cycle tyres are dependent on international markets. Natural rubber can be produced only in tropical areas and high-quality tyres are manufactured in a limited number of industrialised countries. The waste management stage is also increasingly subject to international trade. The knowledge on the commodity and regional patterns of international trade in tyre and tyre derived rubber waste, however, is scant (UNCTAD, 1996). Based on a rather short time series Table 2 demonstrates how both in absolute and relative sense trade of old tyres have become more important in the 1990s.

Table 2
World trade in tyres (in metric tons)

Commodity	1991	1997
New pneumatic tyres	1 894 089	4 635 631
Old tyres pneumatic tyres	297 966	907 233
Share of old tyres in world trade	13.6%	16.4%

Old tyres are defined as the sum of retreaded and used tyres. Source: COMTRADE, UNCTAD.

Frequent reporting in the media about incidents of illegal dumping of Western worn out tyres in low income countries implies that there are large North–South (global level) and West–East (European level) trade flows of used tyres and tyre related rubber waste. Table 3 reports the movement of international trade between developed (North) and developing countries (South). Although the South has expanded imports of old tyres from 16% in 1991 to 27% in 1997, the North–North trade flow still dominates global trade by accounting for almost 73% of the imports. The scarce information on West–East flows indicates that the share of imports of old tyres by Eastern European countries in Europe expanded from 19% in 1992 to 47% in 1997. Note that for Eastern Europe only information has been found for the Czech Republic, Hungary and Poland. For passenger car and truck tyres this share of Eastern European countries in the overall European imports increased only from 4 to 7% and 7 to 14%, respectively (IRSG, 2000). Based on this trade information on North–South and West–East trade it can be concluded that trade of old tyres with neighbouring countries still dominates. Transport costs of the bulky tyres still seem to be a crucial factor.

As elaborately discussed in Van Beukering (2001), several arguments exist for the increasing flow of tyres from high to lower income countries. First, due to the low wage level and the relatively simple process of retreading and recycling, low-income countries may have a comparative advantage in the labour intensive retreading and recycling of tyres. Second, many tyres are imported for reuse

Table 3
Direction of world trade in old tyres (in metric tons)

Direction	1991	1997
From North to North	214 536 (72.0%)	532 546 (58.7%)
From North to South	39 332 (13.2%)	183 261 (20.2%)
From South to North	35 160 (11.8%)	126 105 (13.9%)
From South to South	8939 (3.0%)	64 414 (7.1%)

Source: COMTRADE, UNCTAD.

purposes. Safety standards regarding minimum tread depth and enforcement of these standards are less strict in low-income countries. Third, international differences in disposal fees promote trade of old tyres that are not reusable or retreadable. Because disposal fees are much lower in low-income countries it is a lucrative business to collect tyres in the North, collect the disposal fee paid for by consumers in the North, and export these tyres to low-income countries. For example, the disposal fee in the Netherlands is more than double the fee in the Czech Republic (Rosendorfová et al., 1998). To prevent these practices a trend towards harmonisation of environmental costs in Europe is taking place (Brisson, 1997).

2.5. Selected international issues

In the previous sections an overview has been provided of the most important issues contributing to environmental pressure in the tyre life cycle. In this paper the main focus is on those aspects in the life cycle that have an impact on international trade of used tyres between Western and Eastern Europe. Three issues meet with this criterion: the international difference in waste management policies, the difference in legislation on safety standards and the presence of institutional constraints on trade of used tyres. In the following section, the impact of these aspects will be analysed.

3. A model

International differences between regions in the individual life cycles exist that may have a potential impact on the environmental performance of those regions. These differences can be economic (i.e. labour costs, technological efficiency), institutional (i.e. disposal fees, safety regulations) and social (i.e. environmental preferences, safety awareness). The main focus is specifically on the impact of policy-initiated variations of these differences on the economic and environmental performance of the life cycle of truck tyres.

Before presenting the model we have to clarify the adopted approach. During the formulation and the implementation of the model we had intensive contacts with relevant stakeholders in the tyre industry in Europe. They have provided information on specific relations, data and relevant scenarios for analysis. However, stakeholders sometimes provided different conflicting information on causal relations, and could not provide detailed data on the material flows related to tyres in and between countries in Europe. Due to the lack of solid data, the calibration of the model was focused on dynamic patterns of observed trends. Since many relations and parameters are uncertain, different assumption can lead to the same type of results. Expert judgements of specialists in the tyre industry as used to derive a model that represents our current knowledge of this system. Due to the limitations, the resulting model should be seen as a tool to structure the incomplete available data to explore possible futures by scenario analysis, instead of a solid calibrated model to predict the implications of certain policies.

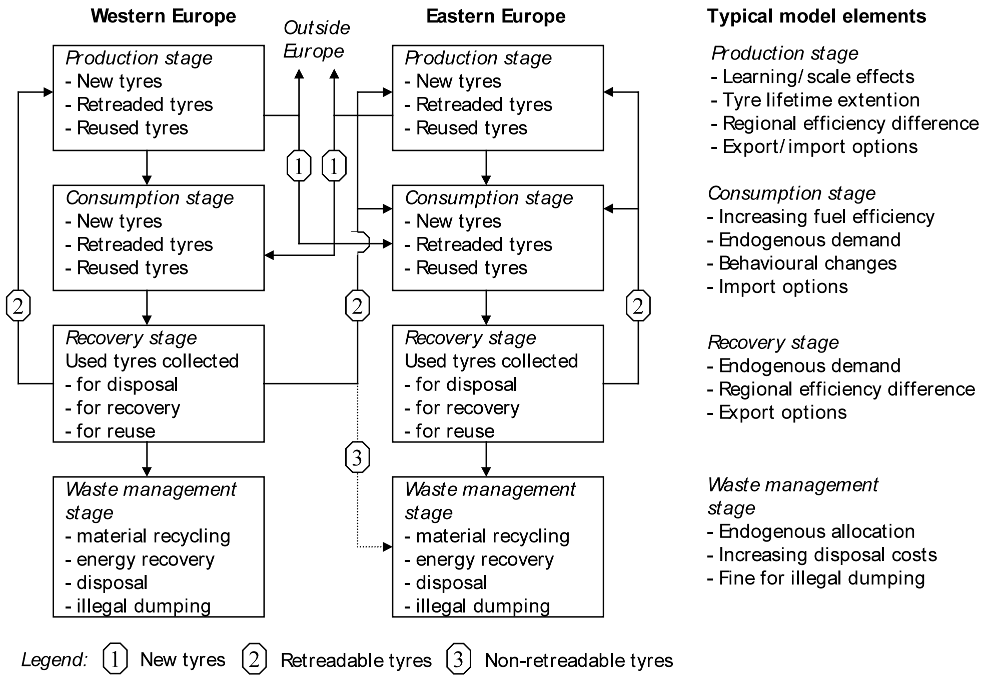

Fig. 2. Structure of the overall model.

3.1. Model structure and characteristics

Fig. 2 depicts the main structure of the system dynamics model that is developed to analyse international changes in the life cycle of truck tyres in Europe. The model has a number of characteristics. To take into account interdependency of different stages, the model incorporates the *complete life cycle* of truck tyres. Changes in one part of the life cycle may have positive or negative consequences in another part. For example, by developing economically feasible waste management options for used tyres, retreading may become less attractive. The net impact for the environment may therefore be negative. Similarly, improving driving behaviour for reasons of fuel consumption can increase the lifetime of a tyre, which subsequently reduces environmental pressure of the production stage.

The material flows in the model are driven by the projected *demand* for tyres. This demand is given as a scenario of metric tons of tyres with the lifetime characteristics of new truck tyres in 1990. The projected demand is corrected for the consequences of change in lifetime of the truck tyre. Each ton of produced and consumed truck tyre finally ends up in landfills or recovered materials or energy. In this way, the model takes into account the mass balance of the tyre life cycle. Within the projected demand the allocation between new, retreaded and reused tyres is determined endogenously, based on the price elasticity of demand and taking into account the availability of reused and retreaded tyres. After the consumption stage old tyres are collected and allocated to disposal, reuse or recovery based on prices and technical possibilities of recovery and reuse. The same holds for allocation of recovered tyres to different forms of recovery.

The model covers *two distinct regions* in Europe and surroundings. Western Europe is characterised by high labour costs, high efficiency, costly solid waste management, and stringent environmental regulations. This region includes Germany, Netherlands, United Kingdom, Belgium, France, and Luxembourg. Eastern Europe is characterised by low wages, low costs for solid waste management and less stringent enforcement of environmental standards. This region includes Poland, Romania, and the Russian Federation. The selection of these countries is based on data availability, the need for similar sized regions, and the trade characteristics of the countries.

Various *interactions* exist between the truck tyre life cycle in Western and Eastern Europe. An exogenous flow of new tyres is traded between both regions. In reality this flow is driven by differences in consumer preferences for certain qualities of new tyres. Retreadable, used tyres are traded from Western to Eastern Europe. Part of this trade flow also is used for direct reuse or is non-retreadable and therefore directly transferred to the waste management sector in Eastern Europe. This share depends on the differences in price used tyres collectors receive from waste managers in both regions. The larger the price difference of the disposal fee in both regions, the more trade in used tyres occurs. Current costs prevent used tyres from moving from Eastern to Western Europe.

Various *dynamic effects* are simulated. Among others, technical and behavioural changes over the long term are accounted for. The model is calibrated for the period 1990–1999 and explores developments for the period 2000–2020. Due to the lack of solid data, the calibration of the model was focused on dynamic patterns of observed trends. Expert judgements of specialists in the tyre industry are used to derive a model that represents our current knowledge of this system. Based on historical improvements an autonomous extension of the lifetime of truck tyres and increase of fuel efficiency of trucks is assumed over time. Learning and scale effects are also incorporated in the new tyre and retreading industry: the larger the cumulative activity level of particular processes the lower costs per unit of output. In other words, importing additional used tyres for retreading improves the comparative advantage of the domestic retreading industry.

Economic and *environmental* effects in the life cycle are accounted for in monetary units. Therefore both impacts are analysed in an integrated manner. Each potential environmental improvement in the life cycle has consequences for the economy. For example, enhancing public awareness with regard to proper tyre pressure requires funds for public campaigns but at the same time generates substantial economic benefits in the long term as a result of reduced fuel consumption. Therefore, to allocate the scarce resources available for environmental management, policy or production measures should also be analysed in terms of the economic consequences.

Fig. 3 illustrates the integration of economic and environmental effects. All economic and environmental impacts are expressed as monetary costs for each stage in the life cycle. The main output variables of the model are private, external and social costs. The social costs are determined by summing the private and external costs. By minimising social costs an optimal situation of the tyre life cycle in Western Europe for the society as whole is achieved. This integration of private and external effects is uncommon in most life cycle studies. A strong advantage of this approach is that it enables the comparison of the benefits of some environmental improvement with the associated costs.

Private costs are defined as costs that are directly accounted for in the tyre life cycle. Private costs consist of costs of using materials, capital, transport, energy, and labour. The costs of materials consist of the sum of prices times inputs of all type of material inputs. Labour costs contain wages paid for unskilled and skilled labour. Energy costs include the costs for electricity. Transport costs result from the distance travelled for each material or tyre type times a fixed price per unit distance. Capital costs per ton tyre are the equal to the amount of capital needed to produce a unit of output. The costs of operation, R and D and marketing are fixed. By-products from the tyre life cycle that fulfil a service outside the tyre life cycle, such as energy from burning tyres in cement kilns, are deduced from the financial costs. Finally, a profit margin factor is added to the cost price to determine the market price. This profit margin factor is determined during (historical) calibration, and is assumed to remain the same in the near future.

The configuration of the costs changes over time for most processes in the tyre life cycle. For example, because labour productivity gradually increases, the share of labour costs in the overall costs of new and retreaded tyres declines. Due to learning by doing, the cost prices drop in time as a linear function of the logarithmic of the cumulated production of retreaded or new tyres. Ultimately these price changes lead to shifts in demand and subsequently lead to reallocation of processes in the tyre life cycle.

External costs are those costs that are caused by activities of agents in the tyre life cycle that have an impact on the another agent's well-being but are not taken into account by the former agent. The procedure to calculate external costs is as follows. Physical input–output matrices for each process in the life cycle are linked to calculate the overall emission levels resulting from the material flows in the life cycle. An example of a physical input–output table is provided in Appendix A. These physical levels are converted into impact levels. Five major external impacts

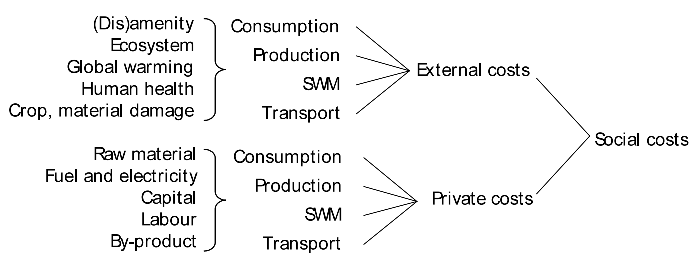

Fig. 3. General cost structure of the model.

are taken into account: human health, global warming, (dis)amenity effects, disturbance of ecosystems, and damage to crops, buildings and materials. These external impacts are ultimately expressed in monetary values. A large number of empirical studies conducting economic valuation for external effects in Western Europe have been used to compile a list of standard values for the most important impacts in the tyre life cycle. In Appendix B an overview has been prepared of the levels of the main external values applied for Western Europe.

It should be realised that these estimates are subject to a substantial amount of qualifications and restrictions. This has consequences for the extent to which the standard values are (generally) applicable. To deal with these restrictions, the instrument of benefit transfer has been presented to facilitate the transfer of the estimates from the Western European external values into values for Eastern Europe. Besides income, demographic and socio-economic factors can be used in the benefit transfer. Another limitation is the assumed linear relation between emission levels and its impact. Although in reality some of these relations are non-linear, valuation studies such as EC (1999) have shown that this simplifying assumption does not lead to unacceptable or fundamental differences in the estimations of the external costs.

3.2. Model description

To illustrate the main features of the simulation model the basic equations that describe the stocks and flows of tyres within Western Europe we and Eastern Europe ee are presented. The description refers to one region but is applicable for both regions. The life cycle of tyres is simulated in terms of metric tons of tyres. The allocation of material flows across the life cycle is based on prices and technical constraints. Because demand is the driving variable in the model, the consumption stage is discussed first. Next, the production, recovery and waste management stages are described. Typical model elements as listed in the life cycle in Fig. 2 will also be addressed. Note that the tyre type is denoted as a subscript and the region is indicated as a superscript.

3.2.1. Consumption stage

Prices for truck tyres p_i derived from the production stage determine the demand for each type of tyre. Using a multinomial logit function and the tyre price p_i in combination with sensitivity parameter β the market share ms of each tyre type i is determined. The multinomial logit function is used to describe the accumulation of the individual choices from consumers for a particular type of tyre. The higher β the more sensitive is the market share to price differences between different types of tyre. The value of β is determined during the calibration of the model to historical market shares.

$$\mathrm{ms}^k_{\mathrm{dem},i} = \exp(-\beta \cdot p^k_i) \Big/ \sum_j \exp(-\beta \cdot p^k_j) \qquad \text{for } k = \text{we, ee} \tag{1}$$

The material flows in the model are driven by the projected demand for tyres, T_{demtot}. Demand for each tyre type $T_{\mathrm{dem},i}$ can then be formulated as the market share times the total demand T_{demtot}. This amount is corrected by the fraction of average lifetime of a tyre l_{avg} divided by the lifetime of the specific type of tyre l_i. The lifetime of tyres increases autonomously over time due to technological improvements.

$$T^k_{\mathrm{dem},i} = \mathrm{ms}^k_{\mathrm{dem},i} \cdot T^k_{\mathrm{demtot}} \cdot (l^k_{\mathrm{avg}}/l^k_i) \qquad \text{for } k = \mathrm{we, ee} \tag{2}$$

Because of safety regulation, legislation restricts reuse of tyres, which is simulated by assuming a maximum fraction of tyres being supplied for reusing tyres. The demand for other types of tyres is based on prices.

The type and use of tyres influence fuel consumption of cars. An autonomous and an endogenous part of fuel efficiency improvement are distinguished. The minimal friction of the tyre causes the autonomous part of the fuel consumption. The pressure of the tyre determines the endogenous part. The fuel efficiency declines at an increasing scale the more the pressure deviates from the optimal pressure.

Fuel consumption F_{C} is defined as the ratio of distance travelled per year by the average truck tyre kmyr divided by the fuel efficiency $F_{\mathrm{E},}$ multiplied by a factor reflecting the difference between the actual and the optimal tyre pressure, multiplied by a factor that attributes the fuel consumption to 1 metric ton of tyre. In case of an optimal pressure of tyres, 85% of fuel consumption is not related to the tyre. This amount is subtracted from F_{C} to determine only the tyre-related consumption.

$$F^k_{\mathrm{C}} = (\mathrm{kmyr}/F^k_{\mathrm{E}}) \cdot (1 + f(T_{\mathrm{pressure}} - T_{\mathrm{optimalpress}}))/4.5 \qquad \text{for } k = \mathrm{we, ee} \tag{3}$$

In this study, the pressure management in both regions is assumed to be the same. The only difference in fuel consumption is caused by the smaller fuel efficiency in Eastern Europe compared to Western Europe.

3.2.2. Production stage

The production P_i of reused tyres (or retreaded) tyres is the minimum of the available tyres $T_{\mathrm{av},i}$ collected for reuse (or retreading) and the demand for reusable (or retreaded) tyres. The demand is region specific, partly determined by domestic legislation. The availability is European-wide because trade of reusable and retreadable tyres is allowed.

$$P^k_i = \mathrm{MIN}(T_{\mathrm{av},i}, T^k_{\mathrm{dem},i}) \qquad \text{for } k = \mathrm{we, ee} \tag{4}$$

The production of new tyres is then the total demand less the production of reused and retreaded tyres. The stocks of the different type of tyres T_i increase due to the production of tyres P_i and decrease through depreciation of tyres using a lifetime $l_{\mathrm{t}i}$:

$$dT^k_i/dt = P^k_i - T^k_i/l^k_{\mathrm{t}i} \qquad \text{for } k = \mathrm{we, ee} \tag{5}$$

The lifetime is assumed to be a function of tyre pressure t_{pres} average lifetime in travelled distance (km) l_{tkm} and the average distance travelled per year (km/year) adt.

$$l_{ti}^{k} = f(t_{\mathrm{pres}}^{k}) \cdot l_{\mathrm{tkm}}^{k}/\mathrm{adt} \qquad \text{for } k = \mathrm{we,\ ee} \tag{6}$$

where the function $f()$ defines that the maximum lifetime is met at an optimal tyre pressure. If the pressure deviates from the optimal pressure, the lifetime of the tyre decreases.

The flow of old collected tyres from Western to Eastern Europe, $T_{\mathrm{old,export}}$, can be formulated as:

$$T_{\mathrm{old,export}} = T_{\mathrm{old}}^{\mathrm{we}} \cdot \frac{\exp(\gamma \cdot (p_{\mathrm{tr}}^{\mathrm{ee}} + b))}{\exp(\gamma \cdot (p_{\mathrm{tr}}^{\mathrm{ee}} + b)) + \exp(\gamma \cdot p_{\mathrm{re}}^{\mathrm{we}})} \qquad \text{for } k = \mathrm{we,\ ee} \tag{7}$$

where $T_{\mathrm{old}}^{\mathrm{we}}$ is the total collected old tyres in Western Europe, is the average price a collected receives for old tyres, b is a bonus for exporting old tyres for further treatment to Eastern Europe, and g is the sensitivity parameter to determine the allocation of old tyres.

3.2.3. Recovery and waste management stage

Each year a number of tyres are depreciated. The total amount of used (old) depreciated tyres T_{old} is defined as the sum of the tyre stock divided by the lifetimes of the various types of tyres. The amount of collected tyres in Western Europe is allocated to both Eastern and Western Europe for further treatment. This allocation is based on the average price waste collectors in Western Europe derive when tyres are allocated to Eastern or Western Europe. Adding a bonus on the average price that can be received in Eastern Europe stimulates export to Eastern Europe.

In each region the used tyres are allocated among illegal dumping, collection for disposal, collection for recovery and collection for reuse. This allocation is based on price differences: the used (old) tyres are allocated to the cheapest possible option. The price collected from agents retreading tyres or reusing tyres are related to supply. When supply of retreaded or reused tyres exceeds the level of the reference scenario, the price derived by collectors drop. The price of illegal dumping is related to the expected fine to be paid. This allocation process of the involved agents is simulated by a multinomial logit function. The price of each option for used tyres p_i and price sensitivity parameter α determine the market share ms_i of treatment of used (old) tyres.

$$\mathrm{ms}_i^k = \exp(-\alpha \cdot p_i^k) \Big/ \sum_j \exp(-\alpha \cdot p_j^k) \qquad \text{for } k = \mathrm{we,\ ee} \tag{8}$$

Besides prices, the ability of old tyres to be retreaded or reused determines the allocation of used tyres. Therefore, the price-dependent allocation has been corrected for this factor. When demand for reused tyres exceeds the maximum technical level, only the share of technical possible tyres $\max_{\mathrm{reuse,new}}^{k}$ from new tyres and $\max_{\mathrm{reuse,recov}}^{k}$ from recovered tyres is reused. The amount of tyres collected for reuse is then defined as:

$$\begin{aligned} T_{\mathrm{reuse}}^{k} = {} & T_{\mathrm{new}}^{k}/l_{\mathrm{new}}^{k} \cdot \mathrm{MIN}(\max_{\mathrm{reuse,new}}^{k}, \mathrm{ms}_{\mathrm{reuse}}^{k}) \\ & + T_{\mathrm{recov}}^{k}/l_{\mathrm{recov}}^{k} \cdot \mathrm{MIN}(\max_{\mathrm{reuse,recov}}^{k}, \mathrm{ms}_{\mathrm{reuse}}^{k}) \qquad \text{for } k = \mathrm{we,\ ee} \end{aligned} \tag{9}$$

Because both technical and price information are used to determine the reuse of tyres, the price dependent market share of Eq. (8) has to be corrected. Therefore, the desired levels of the other destinations of old tyres are corrected by a factor c, such that T_{old} is equal to the sum of the possible treatment of old tyres. This factor is defined as:

$$c = (T^k_{\text{old}} - T^k_{\text{reuse}})/(T^k_{\text{old}} \cdot (1 - \text{ms}^k_{\text{reuse}})) \qquad \text{for } k = \text{we, ee} \tag{10}$$

This leads to Eq. (11) where i consists of collection for disposal, collection for recovery and illegal dumping:

$$T^k_i = \text{ms}^k_i \cdot T^k_{\text{old}} \cdot c \qquad \text{for } k = \text{we, ee} \tag{11}$$

The allocation of recovered tyres retreading, material recycling (granulate), energy recovery and material reuse (rubber pieces) is defined in the same way as allocating old tyres to different treatments. Prices determine a desired allocation, which is corrected by technical constraints. For example, retreading is technically constrained depending on whether the old tyre was a newly produced tyre, a retreaded tyre or a reused tyre.

4. Scenarios and results

Numerous technical, economic and institutional differences exist between the truck tyre life cycle in Western and Eastern Europe that cause different types of trade flows to emerge. Also in terms of environmental stringency both regions differ. The disposal fees and safety standards in Eastern Europe are many times lower than in Western Europe. These conditions are said to lead to significant environmental damage due to the dumping of used tyres in Eastern Europe. Moreover, the Western European industry complains of a lack of incentive of waste managers to support and for tyre collectors to supply the recycling industry in the West.

There are various ways to avoid such effects to occur. One can either eliminate the differences in environmental standards or one can simply ban the trade of used tyres. Three scenarios simulating these interventions are tested and compared with the current situation (the base case). These scenarios are indicated by industrial and policy stakeholders to represent the most plausible policy measures to prevent undesirable conditions in the European tyre life cycle in the coming decades. The exact content of the scenarios is based on interviews with agents in the waste management industry (Rosendorfová et al., 1998), reports on government involvement (Environment Agency, 1997) and personal communication with tyre manufacturers. The scenarios may cause shifts in the national and international material flows of the life cycle of Western Europe (WE) and Eastern Europe (EE). The following scenarios are conducted.

Base case scenario: Technological improvements in both WE and EE are extrapolated based on the current rate of change: the durability of truck tyre and the fuel efficiency of trucks improves each year by 0.6 and 1.5%, respectively. Consumer behaviour remains unchanged in the base case. The tyre life cycles of WE and EE differ in a number of ways. Tyres consumed in EE are on average of a lower quality than in WE and therefore are less retreadable and have a shorter lifetime. Production in EE requires more electricity (10%) and generates more water and air emissions (10%). The costs for labour, electricity, landfilling, intermediates, and externalities are also lower in EE. Because the law on safety (tread depth) is less strictly enforced in EE, more tyres are reused. The monitoring of tyre pressure is worse in EE resulting in higher fuel consumption (7 km/l in WE and 8 km/l in EE in 2000).

Disposal fee harmonisation scenario: At present significant differences exist between disposal fees charged in WE and EE. This cost difference encourages WE collectors to export a large amount of used tyres to EE. The importers in EE purchase the tyres, often at a negative price, sort out the retreadable and reusable tyres and dispose the remaining tyres at rather limited costs. Not only does this create unaccounted environmental externalities in Eastern Europe it also discourages the recycling sector in WE. In the 'harmonisation' scenario the disposal fees in Eastern Europe are increased to the WE level.

Safety law harmonisation scenario: Due to differences in the level and the enforcement of standards, reuse of tyres is a much more popular in EE than in WE. As a result, accidents are more frequent occurring in EE. Moreover, trade of used tyres from WE to EE is claimed to be driven by this difference in regulations. In the 'safety' scenario the rules about the minimum tread depth are adopted from WE.

Trade ban on used tyres: Because tyres produced in EE are of a lower quality, their retreadability is less. The retreading industry is therefore dependent on imports of retreadable imports. At present EE is a major importer of used tyres from WE. A significant share of these tyres is imported for recycling in the retreading industry and in the energy recovery sector. In their support of the 'proximity principal' that is partly the result of the goal to minimise transport, environmental action groups oppose this type of trade. The proximity principle is a guideline of the European Union that recommends member countries to process waste as close to the source as possible (Rosendorfová et al., 1998). In the 'trade ban on used tyres' scenario, the trade of used tyres is prohibited.

The final outcome of these scenarios is presented in various forms. The material flows are reported in terms of production of the various types of tyres. The private, external and social costs are explained for each stage in the life cycle. To facilitate the comparison between the two regions the cost estimates are expressed in € per heavy good vehicle kilometre (HGVkm) for a truck with a capacity of 10 tons. These costs do refer only to the tyre related impact. For the base case scenario absolute figures are reported. Marginal values, representing the difference with the base case, are used for the other scenarios.

4.1. Base case scenario

The base case scenario represents the overall impact of truck tyres on society as currently foreseen for the period 2000–2020. Interference through proactive policy

Table 4
Private and external costs over the life cycle of tyres in Western and Eastern Europe in 2020 (unit: €/1000 HGVkm)

	Production	Consumption	SWM	total
Private costs-WE	4.26 (19.2%)	17.93 (80.7%)	0.02 (0.1%)	22.20
Private costs-EE	4.95 (20.3%)	19.42 (79.5%)	0.06 (0.2%)	24.43
External costs-WE	2.04 (5.0%)	38.95 (95.0%)	0.004 (0.01%)	41.00
External costs-EE	0.64 (2.9%)	21.22 (97.0%)	0.02 (0.1%)	21.87

Note: The share of the costs of each reported stage has been added between brackets.

measures such as public campaigns to improve the monitoring of tyre pressure and the impact of industrial developments such as the introduction of the eco-tyre, have been ignored. The potential impact of these uncertain developments has been elaborately addressed in Van Beukering and Janssen (2000).

Table 4 summarises the private and external costs in the life cycle for the base case scenario in 2020, respectively. Transport costs of materials have been excluded because these are almost negligible compared to the other stages in the life cycle. The external costs are equal or exceed the private costs. This implies that current prices, which correspond to the private costs, do not reflect the true costs for society. Both for the private and the external costs the consumption stage is the dominant process in the life cycle. More than 95% of the external costs occur during the usage of the tyre. This is surprising as most policy interventions in the tyre life cycle focus on waste managers and tyre-manufacturers. This result, however, shows that the consumer is the most powerful stakeholder when it comes to improving the environmental performance.

The private costs in EE are slightly higher than in WE for basically two reasons. First, trucks are less fuel efficient in EE than in WE. Second, despite the lower labour costs inefficiencies in manufacturing of new and retreaded tyres lead to higher overall costs per unit of output. Third, because the collection and processing of used tyres in EE is not as well-developed as in WE waste management is more expensive.

Differences in external costs between WE and EE are caused by several effects. First, the lower valuation of external damage in EE leads to significantly lower external costs in EE. Second, because relatively more tyres are reused in EE the share of production in the external costs in EE is lower than in WE. Reuse of tyres hardly leads to externalities in the production stage. It should be realised that reuse may result in more accidents due to driving on worn out tyres. Because the available data on increased risks are ambiguous, however, this effect has been ignored. Third, for similar reasons as reported in the private costs the share of solid waste management (SWM) in the overall external costs in EE is higher than in WE. A relatively large amount of used tyres is landfill and dumped illegally. This leads to higher external costs than if these tyres would have been recycled.

Table 5 shows the disaggregation of the external costs by type of environmental impact. Because the external costs of eutrophication on ecosystems is rather low it has been excluded from the table. Again one column, human toxicity, dominates by accounting for more than 95% of the total external costs. This high level is caused by the strong relation of human toxicity with transport related emissions. It is particularly the emission of particulate matter (PM_{10}) and nitrous oxide (NO_x) that causes the negative impact on human health. Due to the benefit transfer discount in EE human health damage is valued significantly lower than in the WE.

Global warming is also mainly caused in the consumption and the SWM stage through emissions of carbon dioxide (CO_2) and methane (CH_4). No benefit transfer has been applied to global warming. Since the importance of the SWM stage in EE is higher than in WE the absolute costs also exceed Western levels.

Damage to crop, forest and material has a significant negative net-value because the tropospheric ozone depleting effect of NO_x has a fertilising effect on crops and therefore exceeds the damaging impact of VOC and SO_2 on crop yield. Again no benefit transfer has been applied because these costs are based on real market values. Therefore, the net-negative costs in EE exceed the costs in WE.

Illegal dumping and landfilling mainly causes the external costs for disamenity. Since these practices are more common in EE, the absolute costs are higher in this region. Still the overall disamenity costs are small compared to human health damage.

4.2. Harmonisation scenario

To what extent does the difference in disposal fees of used tyres in EE and WE lead to excessive social costs in both regions? To analyse this effect across the European tyre life cycle, the disposal fees in EE are increased to the level of WE.

Fig. 4 depicts the changes in the physical flows in the harmonisation scenario compared to the base case scenario. Although the direction of change is logical—trade decreases and retreading increases—the size of the shifts in material flows is rather minor. Trade of used tyres from WE to EE decreases only by 2%. The increased costs for disposal in EE results in a long-term expansion of the retreading industry in WE and EE of 4 and 0.5%, respectively. The shift in EE is smaller than in WE because in the base case scenario the retreading industry has already been operating at a relatively high level. The domestic market of retreadable tyres is saturated. Moreover, because the trade flow of retreadable used tyres declined, less imported tyres become available for supply to the retreading market of EE. The increase in retreading is compensated by a decrease in the production in new tyres in both regions.

Table 5
External costs over main impacts of tyres in 2020 (unit: €/1000 vehicle km)

	Human health	Global warming	Crop/material	Disamenity
Western Europe	43.02 (105.2%)	0.51 (1.2%)	−2.65 (−6.5%)	0.004 (0.01%)
Eastern Europe	23.97 (108.7%)	0.73 (4.1%)	−2.85 (−12.9%)	0.02 (0.1%)

Note: The share of the costs of each reported stage has been added between brackets.

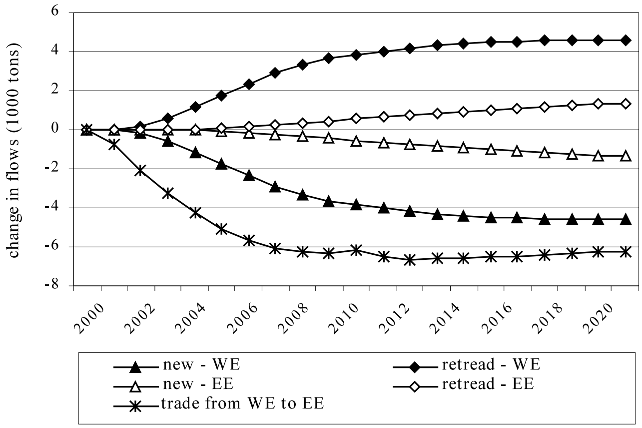

Fig. 4. Change in flows in Eastern Europe (EE) and Western Europe (WE) in new tyre production, retreading and trade in used tyres in the 'harmonisation' scenario (2000–2020).

The question remains whether the harmonisation of the disposal fees does lead to increased welfare. Fig. 5 summarises the social, private and external costs of the harmonisation scenario for the different regions. In social terms, all regions benefit from harmonisation of the disposal fees. This is remarkable because in the first instance one would expect that at least the exporting region of old tyres would suffer from higher disposal fees in the importing region. Note that the private and external transport costs of international trade have been allocated evenly between EE and WE.

The largest improvement is achieved in the private costs in EE. Because the recycling industry in EE in the base case can not compete with the cheap option of landfilling, recycling of worn-out tyres never have developed. Now that the opportunity costs of recycling are lowered, recycling is able to process larger volumes and thereby also decrease the production costs due to the learning effect. Moreover, the retreading industry overtakes a small share of the manufacturers of new tyres. As retreading is cheaper than the production of new tyres the overall costs decrease. The external costs also decrease slightly as a result of these shifts in the life cycle.

The shifts in costs in WE is less pronounced than in EE. This is plausible as the only impact on the life cycle in WE is the reduced option to export used tyres. No major shifts from landfilling to recycling options can occur because landfilling is practically absent in the original situation. Therefore, the only notable effect is a small increase in retreading and in recycling of worn-out tyres. Because the latter activity generates new raw materials and energy, the net impact of this shift is positive the environment: the external costs reduce. Because increased recycling also leads to learning effects for the industry, costs decline and thereby reduce the private costs. A similar impact on the private costs results from the increased use of retreaded tyres in WE.

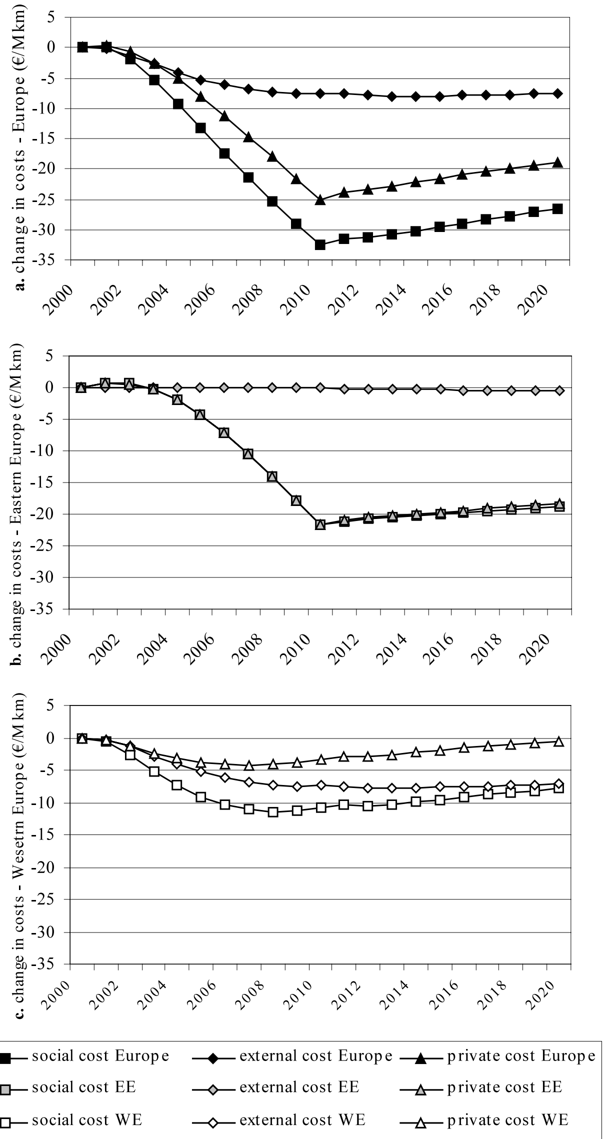

Fig. 5. Social, external and private costs in the 'harmonisation' scenario 2000–2020 in (a) Europe; (b) Eastern Europe—EE; and (c) Western Europe—WE (unit/€Mkm—euro per million heavy good kilometre).

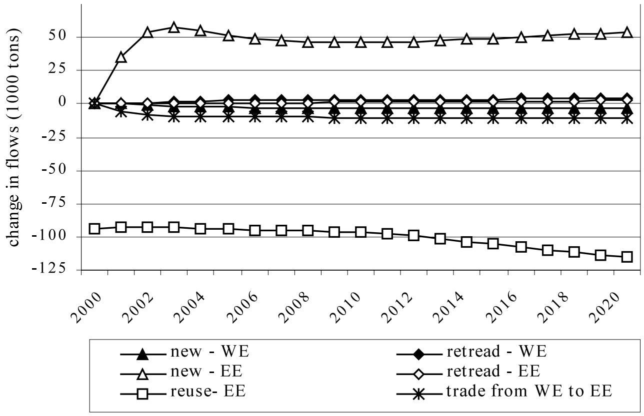

Fig. 6. Change in flows in Eastern Europe (EE) and Western Europe (WE) in new tyre production retreading and trade in used tyres in the 'safety' scenario (2000–2020).

4.3. Safety scenario

Another cause of trade flows of used tyres from WE to EE is the difference in regulations and enforcement of the minimum tread depth of passenger and truck tyres. If a tyre is no longer legal in WE the same tyre can still be reused in EE. The trade of used tyres facilitates the relatively cheap extension of the tyre lifetime but eventually also results in increased waste from worn-out tyres. To verify the extent of this trade-off the standards regarding the minimum tread depth in EE are harmonised with the standards in WE. This scenario is called the 'safety' scenario. Fig. 6 demonstrates the change in physical flows in the European tyre life cycle.

The introduction of strict laws on tread depth in EE has a much stronger impact on material flows than the harmonisation scenario. The new regulations lead to a significant decrease in the reuse of tyres in EE. Increased retreading and production of new tyres compensate for this decline in reuse. Retreading can increase in EE because less tyres have been damaged by reuse. The reduction in trade does not at all relate to the reduction in reuse. This implies that trade of used tyres is only for a small part driven by differences in safety regulations. As the effect on trade is limited, the impact on the life cycle in WE is also minor. As less used tyres leave the region more retreading takes place. In response the requirement for new tyres declines in WE.

Fig. 7 summarises the costs of the safety scenario in overall Europe, Western and Eastern Europe, respectively. The introduction of the new rules does not result in higher welfare in Europe. Instead social costs in Europe increase significantly, especially in the first years after the introduction. The main reason for this unexpected outcome is that the reduced occurrence of accidents has not been accounted for. Also, possible effects on the fuel efficiency have been ignored. No data have been found for this externality.

EE dominates the overall outcome for Europe. As shown in Fig. 7b the private costs increase instantly with the introduction of the new laws. The truck fleet that was previously reusing and regrooving tyres now is forced to buy new tyres. Therefore, in the first 2 years private expenditures increase significantly. This increased demand for new tyres generates learning effects in the tyre manufacturing industry that gradually results in lower prices for new tyres. On the longer term this

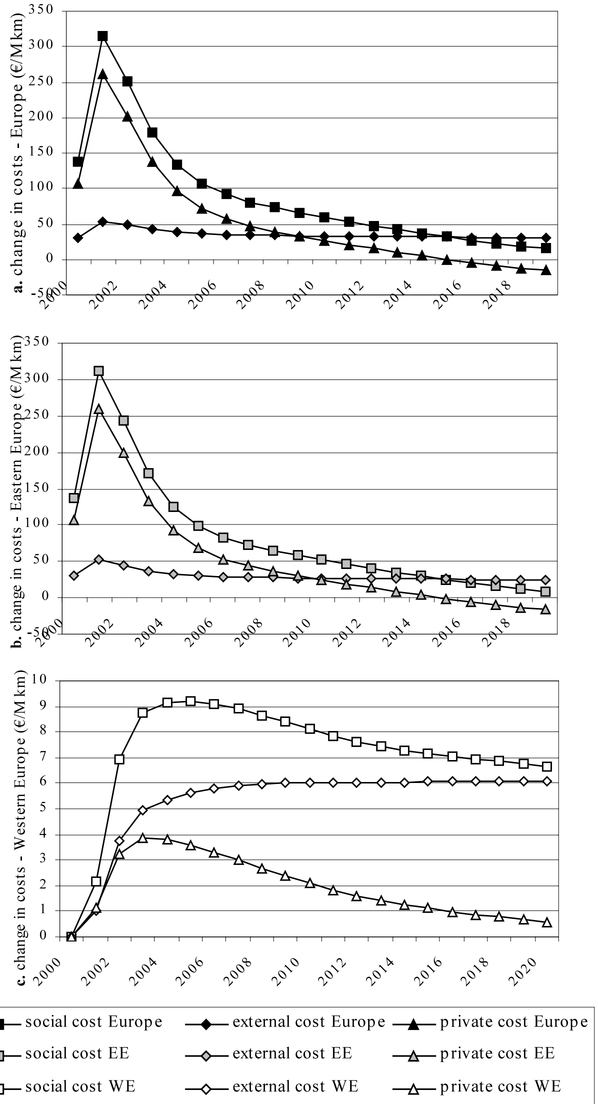

Fig. 7. Social, external and private costs in the 'safety' scenario 2000–2020 in (a) Europe; (b) Eastern Europe—EE; and (c) Western Europe—WE (unit/€Mkm—euro per million heavy good kilometre).

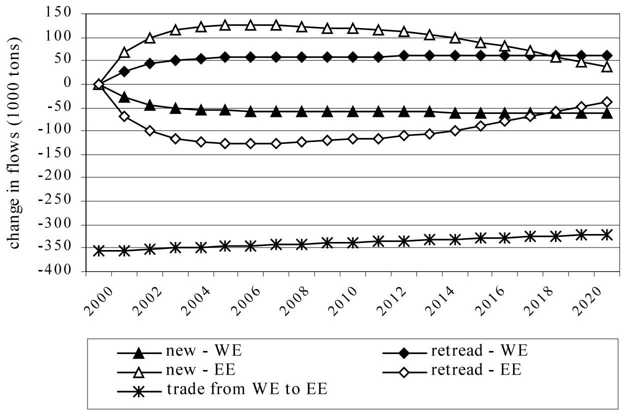

Fig. 8. Change in flows in Eastern Europe (EE) and Western Europe (WE) tyre production retreading and trade in used tyres in the 'no-trade' scenario (2000–2020).

leads to lower private costs than in the base case scenario. The overall private costs for SWM is also lower than in the base case scenario as less tyre waste results per driven kilometre. New tyres last longer and moreover can be re-treaded. The external costs increase because new tyres generate substantially more external effects than the preparation for reuse. The decrease in the external effects of the SWM stage compensates this impact only to a limited extent.

WE is only indirectly influenced by the change in safety regulations in EE: the change in private and external costs is only a fraction of the changes in EE. Part of the previously exported used tyres is retreaded and thereby substitutes new tyres. This has a decreasing effect on the private and external costs in WE. Since part of this previously exported used tyres is unsuitable for retreading, however, more pressure results on the recycling and SWM sector. Therefore the overall private and external costs increase slightly in the safety scenario. Because externalities are valued higher in WE the external costs exceed the private costs.

4.4. No trade scenario

Rather than focussing on the cause of the problem of the tyre life cycle in Europe one can chose to fight the symptom instead. Therefore, an alternative strategy to prevent undesirable effects to occur as a result of differences in environmental standards is to introduce a complete trade ban on export of used tyres from WE to EE. The impact of this 'no trade' scenario on the material flows in the European life cycle are shown in Fig. 8.

EE is impacted most by the trade ban. A significant share of the imported used tyres was originally used for retreading purposes. Therefore, a reduction in supply of castings leads to a decrease in production of retreaded tyres in EE.

This reduction is compensated for by the production of new tyres. Because the lifetime of tyres expands over time, the production of new tyres eventually slows down at the end of the simulated period. The dumping of worn-out tyres in landfills in EE declines by 10% after the ban. Also the recycling industry in EE diminishes.

In WE opposite effects occur. Faced with a significant amount of used tyres, the recycling industry grows by 40%. In the early years after the introduction of the trade ban landfilling of worn-out tyres expands by as much as 15%. The retreading industry is faced with an oversupply of used tyres and therefore can reduce its purchasing price. The production of retreaded tyres expands by almost 40% thereby substituting the production of new tyres.

Fig. 9 summarises the change in social, private and external costs of the 'no trade' scenario compared to the 'base case' scenario. Especially in the first year after the introduction of the trade ban of used tyres the external and private costs increase significantly. This is mainly the result of the abrupt nature of this policy interference. The system requires time to adapt to the new conditions.

The initial shock is also visible in the change in costs in EE (see Fig. 9b). The lack of retreadable tyres is fully met through the production of new tyres. This leads to significantly higher private and external costs. Throughout the years, however, the learning effect results in lower private costs than in the base case. The external effects in EE follow a similar pattern. On the longer term the ban on import of used tyres has formed an incentive for the tyre manufacturing industry in EE to develop faster than they would have done with open borders for used tyres. Although hardly noticeable, the private and external costs of transport decline due to the disappearance of imports.

Fig. 9c shows how the initial shock shifts the tyre production sector in WE from new to retreaded tyres thereby reducing the private and external costs. Similar learning effects such as occurred in EE, however, do not occur. The retreading industry has already been operating in a rather optimal manner and therefore has little to gain from additional experience. The recycling industry, on the other hand, is still in its infant stage during the first years and therefore reduces the costs while simultaneously expanding the production.

Three additional effects occur in WE. First, the sudden introduction of the ban causes both landfill and illegal dumping to increase in the first few years of the covered period. The retreading and the recycling industry require some time to adapt to the new conditions. Second, by extending the lifetime of tyres through increased retreading of tyres, the average vintage of the tyres in use declines. The share of old-fashioned tyres in use is relatively larger. As fuel consumption of newly produced tyres improves gradually, the older the model in use, the higher the energy usage of the average tyre. This so-called 'vintage effect' ultimately causes the private costs to exceed the level in the base case scenario. Third, transport costs reduce due to the absence of export of used tyres. This effect is, however, negligible compared to the other effects.

5. Conclusions

Truck tyres in Europe inevitably generate negative environmental effects. These effects may occur in various stages of the life cycle. An international issue that receives wide attention in the media and among policy makers is the large trade flow of used tyres from Western to Eastern Europe. This flow is often explained as

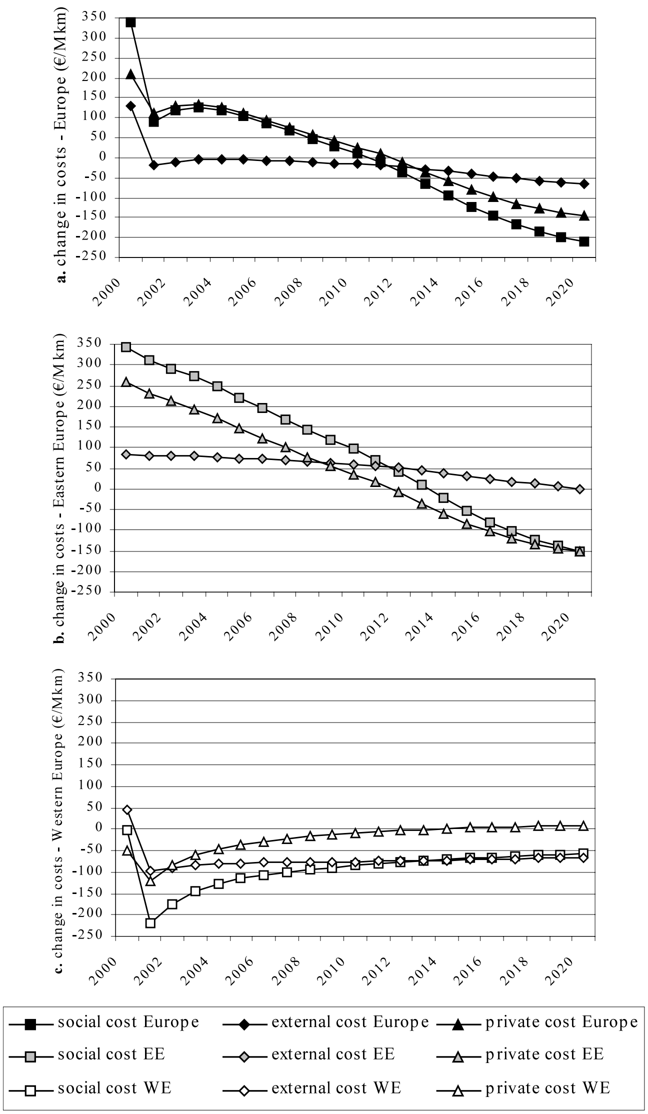

Fig. 9. Social, external and private costs in the 'no-trade' scenario 2000–2020 in (a) Europe; (b) Eastern Europe—EE; and (c) Western Europe—WE (unit/€Mkm—euro per million heavy good kilometre).

the consequence of differences in environmental standards. Disposal fees in Eastern Europe are significantly lower than in Western Europe and safety standards are less stringent thereby allowing traded used tyres to be reused in Eastern Europe. This trade may lead to further environmental damage and is also claimed to cause unfavourable conditions for recyclers in Western Europe. Therefore, without harmonised environmental standards or trade intervention pollution havens are expected to emerge in the European tyre life cycle.

In this study the economic, environmental and social effectiveness of harmonisation and trade measures in the European life cycle for truck tyre is tested. A two-region simulation model is developed that is dynamic in nature, integrates the complete life cycle, incorporates environmental impacts in its economic analysis, and allows for variations in trade of new and old truck tyres. The two regions represent Western and Eastern Europe. The model has several advantages. First, by modelling endogenous demand and supply in various stages of the life cycle, the model calibrates a realistic representation of the current conditions of the market for truck tyres in Europe. As a result the trade flows of used tyres can be estimated.

Second, rather than presenting these criteria as separate outcomes, the model allows for a trade-off between private (economic) and external (environmental) effects because both impacts are expressed in monetary units. Finally, the flexible and dynamic nature of the model allows for the incorporation of technological, economic and institutional changes in the tyre life cycle. Therefore, even complex processes such as scale and learning effects can be accounted for.

Although our simulation model has appealing advantages compared to more frequent used static analysis of material flows, there are a number of serious limitations. The for-mutation of the model was limited by the current knowledge on various causal relationships, for example the impacts of using retreated tyres on safety of cars. The implementation of the model was complicated by the scarce amount of reliable data. Furthermore, we focused on the flows of tyres in Europe, while it might be expected that flows of recyclable materials to developing countries become more important in the future (Van Beukering, 2001). Given the limitations of our approach we can not make precise predictions but use the model as a framework to analyse the current available information for exploration of different policy scenarios.

Several conclusions can be drawn from the model simulations. The consumption stage is accounts for the majority of the overall external effects of truck tyres. Trade has no impact on the consumption stage. Therefore, the environmental effects caused by the trade of used tyres from Western to Eastern Europe are limited. Policies aiming at the reduction of the overall environmental damage caused by truck tyres should therefore primarily focus on interventions in this stage of the life cycle, for instance, by improving the management of tyre pressure.

Harmonisation of disposal fees illustrated to generate limited positive results. The private and external costs in the SWM stage are too limited to have a strong impact on the overall configuration of the European tyre life cycle. The introduction of strict laws on tread depth in Eastern Europe has a much stronger impact on material flows than the harmonisation scenario. Rather than intervening at the end of the cycle, this scenario focuses on the consumption stage. The private costs of increased safety, however, dominate the welfare effects. As a result, the social costs increase. Only in the long term, when learning effects have resulted in lower costs in the retreading and new tyre industry, do stricter regulations on tread depth result in less negative welfare effects. The sudden introduction of a trade ban on used tyres in the first instance also increases the social costs in Europe. On the longer term, when alternative destinations for the previously traded used tyres have been developed in Western Europe and additional capacity of new tyre producers have been established, does the overall welfare benefit somewhat from the trade ban.

This outcome indicates that undesirable trade only results from incorrectly priced production factors or institutional failures. Policy measures are most effective in reducing the external costs of the European tyre life cycle by addressing these distortions directly. In other words, the polluter pays principle needs to be applied. If Eastern Europe wants to avoid used tyres from Western European to be dumped on their landfill sites or to be used by their citizens, domestic disposal fees need to be increased and safety regulations need to be strengthened. By directly limiting trade of used truck tyres the private and external gains of trade are lost. Trade bans of used truck tyres fight the symptom and not with the cause of external costs.

Acknowledgements

This research was done in the context of the research programme ‘Materials Use and Spatial Scales in Industrial Metabolism’ (MUSSIM), funded by the Netherlands Organisation for Scientific Research (NWO). See also http://www.econ.vu.nl/re/mussim/mussim.htm. The authors thank Jeroen van den Bergh and Harmen Verbruggen for their useful comments.

Appendix A. Input–output matrix

The technologies applied in the model are based on Best Available Technologies (BAT) for all processes in the cycle. Associated with each process is a vector, also known as a technology matrix, which describes the various inputs and outputs. The table below gives an example of a technology matrix for feedstock recycling. The individual processes are linked through a series of mass balance equations that stipulate that total mass of material used equals total mass of material produced. The transportation logistics are also taken into account. By linking the various stages in the cycle through a series of material balance flow equations, the level of raw, intermediate, final and pollutant goods used and produced can be computed.

Example of an input–output matrix for tyre retreading

		Quantity	Unit
Input	Mixed waste		
	Plastics	1000	kg
	H_2	34	kg
	Labour	4	Man-hour
	Electricity	28.2	GJ
Output	Syngas	67.6	GJ
	CH_4	0.14	Kg
	CO	0.066	Kg
	CO_2	499	Kg
	HC	0.016	Kg
	N_2O	0.003	Kg
	NO_x	0.094	Kg
	SO_2	0.054	Kg
	Solid waste	19	Kg

Source: CE 1997.

Appendix B. External values

The contribution of the range of pollutants to the external costs is expressed in monetary terms. These values have been derived from various studies. An overview of these studies is provided in Van Beukering (2000). The table below summarises the selected values applied in this study.

Externalities new estimates

Impact category	Pollutant	External value-Western Europe	Unit
Global warming[a]	CO_2	2.40	€/metric ton
	N_2O	748.3	€/metric ton
	CH_4	44.9	€/metric ton
Human health[b]	SO_2 production	7204	€/metric ton
	NO_x production	3432	€/metric ton
	PM_{10} production	23 683	€/metric ton
	VOC production	734	€/metric ton
	HC production	602	€/metric ton
	SO_2 transport	6401	€/metric ton
	NO_x transport	3154	€/metric ton
	PM_{10} transport	87 258	€/metric ton

	VOC transport	602	€/metric ton
	CO transport	0.71	€/metric ton
	Benzene transport	554	€/metric ton
	Accidents transport	32	€/1000 HGVkm
Crop material damage[b]	SO_2	215	€/metric ton
	NO_x via ozone	−697	€/metric ton
	VOC via ozone	642	€/metric ton
Disamenity[c]	Non-hazardous waste	37	€/metric ton
	Hazardous waste	370	€/metric ton
	Congestion	171	€/1000 HGVkm
Ecosystem[b]	BOD	240	€/metric ton
	COD	240	€/metric ton
	TSP	24	€/metric ton
	N	4000	€/metric ton

[a]Tol (1999).

[b]EC (1999).

[c]Brisson and Pearce (1995) for disamenity values of landfilling and Brossier (1996) for external costs of congestion.

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