The Design and Implementation of Driving Time Regulation

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Our object of study is welfare optimal driving time regulations in professional road transportation. Due to fatigue, traffic accident risks are supposed to increase as driving times rise. Conversely, the quantity and quality of road infrastructure affect productivity and safety in transportation positively. As the typical driver does not bear all the social costs when accidents happen, in the absence of public regulation, she has an incentive to drive too many hours. Hence, we present two types of public regulatory tools: a uniform driving time restriction and a uniform tax. We then compare the likely outcomes of these regulations (second-best policies) with the welfare optimal (first-best) solution. Moreover, as driving time restrictions are commonly applied worldwide, we study the problem of implementing such prescriptions. When public authorities choose optimal resources in driving time restrictions, the detection of the flouting of these restrictions and the penalty levels for non-compliance, the welfare gains involved must balance the direct and indirect enforcement costs. For example, it follows that the welfare-optimal penalty level should not be so high that the most efficient companies are always forced to comply with the uniform driving time restriction.

Keywords:
Driving and resting time restrictions, traffic safety, road transportation, moral hazard, optimal enforcement policy

1. Introduction

National and international public authorities regulate the professional conveyance of passengers and goods on the roads which affects transport companies' profitability. National authorities have a responsibility to build and maintain roads. The sizes, dimensions and quality of these roads are important for effective and safe conveyance. Additionally, professional road drivers are subject to specific rules concerning hours of driving and resting, which are more restrictive than the ordinary working time rules that generally apply in the labor market. The specific regulation of driving and resting time is identical for all EU/EEA-countries, and the same type of rules – defining maximum hours of service and

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driving time – apply in other countries as well. The time regulation ensures that drivers do not stay on the road for too many hours, possibly inviting fatigue and increasing the risk of traffic accidents. Additionally, time regulation secures drivers' working conditions and ensures fair competition in transport markets – see for instance Newnam and Goode (2015).

Regulations to ensure the safety and soundness of the transportation system are necessary due to the systematic negative effects of transport production that affect many people who are not directly involved as parties in a particular transport activity. Government interventions to prevent different types of externalities deriving from transportation (such as global and local pollution, queuing and overcrowding, accident costs) take a variety of forms. Interventions in the road conveyance industry include the following: a) supplying infrastructure and services, b) restrictions on particular behaviors and c) taxes/subsidies designed to induce appropriate behavior. Regulation restricts an individual or a company from doing what they otherwise would have done, and these restrictions are necessary because of discrepancies in social and private costs and benefits. General discussions on the regulation of externalities can be found in Arnott and Stiglitz (1986) and Stiglitz and Rosengard (2015). The enforcement problem is treated generally by Garoupa (1997) and Polinsky and Shavell (2000), and is discussed in the context of speed regulation by Jørgensen and Pedersen (2005), Ryeng (2012) and Schechtman et al. (2016).

In reality there are many factors affecting the probability of accidents – see for instance Newnam and Goode (2015) and Thompson et al. (2015) and the references therein. In a study of 130 fatal accidents involving heavy vehicles in Norway, Assum and Sørensen (2010) conclude that, in the head-on accidents where these vehicles were responsible, factors like speed, error, fatigue and inattention were decisive. In common with many other studies, Soccolich et al. (2013) found in their empirical investigation that accident risks increase with the amount of driving and working hours due to compromised concentration and alertness among the drivers. There is now a widespread consensus on the need for driving and resting time regulation to prevent fatigue among drivers and thus reduce the risk of traffic accidents on the roads, see also Arnold et al. (1997), Freyer et al. (1997), Ragnøy and Sagberg (1999), Amundsen and Sagberg (2003), Erke and Elvik (2006), Askildsen (2011), Stevenson et al. (2013) and Phillips et al. (2015).)

The actual regulation in Europe has detailed requirements.[3] Firstly, the total daily driving period shall not exceed 9 h, although twice a week it can be extended to a maximum of 10 h (Article 6(1)). Secondly, the total weekly driving time may not exceed 56 h, and the total fortnightly driving time may not exceed 90 h (Article 6(2)). Thirdly, breaks must be at least 45 min, which may be separated into a break of 15 min followed by one of 30 min, and should be taken after 4.5 h at the latest (Article 7). Fourthly, the daily rest period shall be at least 11 h, although three times a week it can be reduced to 9 h (Article 8(2) and (4)). Finally, the weekly rest period is 45 continuous hours, although it can be reduced to 24 h (Article 8(6)).

Even though the aforementioned studies reveal the need for driving and resting time regulations in road transportation, we do not know of any economic model that discusses the problem of designing and implementing such a policy. However, many studies have been conducted on different regulatory tools designed to reduce safety critical events and accidents on the road – see for instance Persson and Ödegaard (1995), Peirson et al. (1998), Jara-Diaz et al. (2000), Dickerson et al. (2000), Benthem (2015). These works focus on issues

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[3]The regulation is defined in EU No 651/2006 (Sitran and Pastori, 2013).

like drivers' speed and concentration levels and the state of the roads and vehicles. Some authors have also analyzed models where technological safety improvements of roads and vehicles may induce individual agents to be less careful than they were before – see for instance O'Neill (1977), Wilde (1982), Blomquist (1986), Janssen and Tenkink (1988), Risa (1992, 1994), Jørgensen (1993), Jørgensen and Polak (1993) and Jørgensen and Pedersen (2002). A similar tradition has been to model the actual interactions among several road users and the carefulness of their decisions when trying to understand what determines traffic accident risk. In such game theoretical models, a transport user's choice of action is directly affected by the other transport users' behavior, and all actions together influence the accident risk; see, for instance, Prentice (1974), Shavell (1980, 1982, 1984), Lee (1984), Boyer and Dionne (1987), Pedersen (2003), Sugden (2004), Savage (2011) and Andersson and Auffhammer (2013).

Inspired by the empirical literature on driving time regulations and the earlier economic models of traffic safety, we propose an economic model to design and implement driving time restrictions for professional drivers. To analyze the rationale for driving time regulations, in section 2 we establish a simplified economic model for N heterogeneous professional drivers choosing operating times on the roads. Given these commercial actors' private incentives to choose driving times that maximize profits, we examine the public regulator's problem of designing policies to secure the highest possible level of welfare. First, we deduce the best solution regarding the supply of public services, assumed to influence every company's profitability and the accident risk, and the optimal driving time for each transport operator's welfare. As the regulator lacks detailed information and the power to determine driving times, we deduce and discuss different types of second-best polices. Firstly, we analyze the case where the regulator establishes a uniform driving time restriction. Secondly, we study the case of a uniform taxation of the companies' actual choices of driving times, and compare the outcomes from uniform driving time regulation and uniform taxation. In section 3 we add to the analysis the regulator's problem of enforcing the driving time limit. We consider companies that find it advantageous either to comply with the rule or break it. Section 4 sums up the analyses, describes some policy implications, and offers some critical comments and ideas for further research.

2. Model

We consider a typical transport company i, facing an exogenous production technology given by equation (1) below. It describes the net revenue (operating profit) for company i per period, R^i, as a linear function of the firm's decision variable, driving time per period, t^i:

$$R^i(t^i) = q^i(g)t^i, \text{ where } q^i_g > 0 \text{ and } q^i_{gg} < 0 \tag{1}$$

where g symbolizes the authorities' supply of public goods, positively affecting the firms' revenues. This specification means that, for simplicity, we ignore all inputs other than driving time, which the firm normally controls and adjusts. It follows from (1) that $q^i(g)$ can be interpreted as company i's net revenue per hour driving, or marginal revenue minus marginal operational costs.[4] Generally, net revenue may vary between companies due to

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differences in market conditions, companies operating different types of transport, divergencies in company-specific technology and varying labor costs. Public supply of infrastructure and services (for instance road standard, road maintenance, parking and resting facilities) is, for simplicity, modelled as a uniform variable. It follows directly from (1) that g becomes a public good.[5] The net revenue per hour driving is supposed to increase as public spending is increased, $q_g^i > 0$, but the increase becomes steadily smaller as g grows, $q_{gg}^i < 0$.

In addition to ordinary operational costs, the company incurs extra costs if an accident occurs. Let us assume that we can formulate the accident probability function for company i as follows:

$$p^i = p^i(t^i, g), \text{ where } p_t^i > 0, p_g^i < 0, p_{tt}^i > 0, p_{gg}^i \geq 0 \text{ and } p_{tg}^i \leq 0 \qquad (2)$$

The probability for a transport company being involved in an accident is supposed to increase as driving time by the company increases due to reduced concentration and alertness among drivers as the time on the road increases, i.e., $p_t^i > 0$. Furthermore, we assume that the public authority reduces the probability of an accident by supplying more infrastructure and services, i.e., $p_g^i < 0$. In addition, it seems reasonable to assume that the change in the probability of an accident due to a marginal change in driving time increases as total driving hours rise. Thus, it becomes riskier to step up driving time the more hours the driver has already been on the road, $p_{tt}^i > 0$. Furthermore, as the supply of the public good becomes higher, we assume the marginal safety-improving effect of the public good decreases, i.e., $p_{gg}^i \geq 0$. Finally, it seems reasonable to assume that increased public supply reduces the marginal safety-worsening effect of driving time, i.e., $p_{tg}^i \leq 0$. For the sake of simplicity, we have ignored that the accident risk for a driver might be (slightly) dependent on all other drivers' behavior. Furthermore, let L_I^i be the private costs company i experiences if an accident occurs, termed the internal loss. To simplify, we consider these costs to be unaffected by other variables in our model. This internal loss measures such factors as costs of damage to vehicle and cargo, downtime, lost assignments, and further negative internal economic costs covered by the company if an accident occurs.[6]

2.1 Companies' optimal behavior in the absence of public regulation

Given equations (1) and (2), we can now define the expected profit for the transport company i as:

$$\pi^i = q^i(g)t^i - p^i(t^i, g)L_I^i \qquad (3)$$

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operational costs per Tkm). Total driving time (hours per month) is *t=d+b,* where *d* is driving time with load and *b* is without load (empty vehicle). Assume that hours of 'empty driving' is a fixed proportion, *μ,* of total driving time, *b =μt.* Suppose now that *z* is the average speed of vehicle driving (with and without load), then the company's production volume will be *y=vz(1-μ),* and the company's net revenue is *R=qt,* where *q=hvz(1-μ),* i.e. equation (1).

[5] For instance, *g* could be a variable measuring the public resources used in improving the standard of roads, where these improvements would make it possible to increase average speed (*z*) among all operators for a given net revenue per Tkm (*h*) and a given transport volume (*v*). Alternatively, improvements in the standards of roads would make it possible to reduce operating costs and thereby increase net revenue per Tkm (*h*) for a given average speed (*z*), and given transport volume (*v*), see also footnote 2.

[6] We do not explicitly model and discuss the possibility of private insurance. This means that the firm, insured or not, has to cover at least some of the private losses should an accident occur.

The transport company adjusts driving time to maximize expected profit, given the public supply of infrastructure and services, g. The necessary and sufficient conditions securing the maximum expected profit for company i become the following:

$$q^i(g) = p_t^i(t^i, g)L_I^i \quad \text{and} \quad p_{tt}^i L_I^i < 0 \qquad (4)$$

The expressions in (4) are standard maximizing conditions. The marginal revenue equals expected marginal costs at the optimum. The concavity of the expected profit function is satisfied due to the assumption in (2) that the accident probability function is convex in driving time. The optimal driving time for company i depends on the internal loss and the supply of the public good. Thus, (4) implicitly defines the optimal driving time, t_*^i, as a function of internal loss and the size of the public good supplied, i.e., $t_*^i = t_*^i(L_I^i, g)$, where it follows from (4) and the assumptions made in (1) and (2) that $\frac{\partial t_*^i}{\partial L_I^i} = \frac{p_t^i}{p_{tt}^i L_I^i} < 0$ and $\frac{\partial t_*^i}{\partial g} = \frac{q_g^i - p_{tg}^i L_I^i}{p_{tt}^i L_I^i} > 0$. From these expressions, it is seen that the companies' optimal driving time decreases as internal loss increases and that more public service, g, results in longer driving times. From the nominator in the second inequality, we see that two effects are involved. The first term is the net revenue effect of better public infrastructure. The second effect shows that increased public goods might also reduce companies' expected accident costs, meaning it might be profitable for the transport company to increase driving time. This last effect is an unintentional result of better public infrastructure, and this effect is often termed a moral hazard effect or a risk-compensation effect; see for instance, Peltzman (1975).[7]

The internal loss is not the only relevant factor in the case of accidents. We define L^i as the sum of the internal loss, L_I^i and the external loss, L_E^i. In general, private actors on the roads have limited liabilities for accident costs. We suppose that the external loss if an accident occurs, L_E^i, includes all costs experienced by the society outside the company. For instance, this loss might include rescue operation costs, costs caused by traffic delays and costs affecting other companies, such as lost reputation among customers and more expensive accident insurance. In addition, this loss also measures costs for households that might experience negative economic and social consequences if the accident causes fatal or serious injuries to the persons involved. It seems likely that this external loss from different types of accidents and undesirable events involving heavy vehicles is relatively important to society at large and might be higher than the internal loss experienced by the company.[8] The total loss is then the sum of the internal and external loss, i.e. $L^i = L_E^i + L_I^i$.

2.2 The optimal welfare solution

When assuming N transport companies in the industry, the welfare stemming from their activity is defined by the sum of the expected profits minus the sum of the expected external accident costs and the cost of supplying the public good, i.e.. $W = \sum_i (\pi^i - p^i L_E^i) - cg$, where c measures a constant unit price of the public good. Maximizing W as defined above with

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[7] For instance, when considering the influence of differences in motor vehicle insurance, Vukina and Nestic (2015) find empirical evidence for such moral hazard effects.

[8] For instance, during the winter season, roads in Norway are often closed or partly closed due to jammed heavy vehicles. For many such events, the internal loss is often insignificant (for instance, no damages to vehicle and cargo) compared with the total external loss experienced by other road users (delays, queues, and so on.). See Bardal and Jørgensen (2017). Edlin and Karaca-Mandic (2006) estimate substantial external accident costs using US insurance data.

respect to t and g yields the necessary conditions for an optimal welfare allocation of driving time and public supply of infrastructure:[9]

$$\text{(a) } \frac{\partial W}{\partial t^i} = q^i(g) - p_t^i(t^i, g)L^i = 0 \text{ and (b) } \frac{\partial W}{\partial g} = \sum_{i=1}^{N}(q_g^i t^i - p_g^i L^i) - c = 0 \qquad (5)$$

The solution given by (5) determines the socially optimal driving time for each firm, denoted t_S^i, and the socially optimal level of the public good, g_S. Equation (5a) gives the conditions for a truly optimal welfare allocation of driving time by each company in the industry. It follows that the socially optimal driving time varies among companies because of possible differences in marginal net revenues, differences in losses in the event of an accident and generally unequal accident probabilities. Let us compare the optimal welfare conditions in (5) with the condition defining maximum profits for the companies in equation (4). When deciding optimal welfare driving times, one must include external loss in addition to internal loss in order to calculate the relevant costs if an accident occurs. Assuming positive external loss for all companies if an accident occurs, comparing (4) and (5a) shows that, for any given level of public supply, the optimal welfare solution gives lower driving time values than the ones preferred by the companies, i.e. $t_S^i < t_*^i$. According equation (5b) the aggregate value of the marginal product of the public good, g, for all of the operating companies should equal the marginal costs of supplying public infrastructure and services. This condition is the standard efficiency condition in the case of a pure public good. The aggregated marginal value of the public good, g, has two elements. The first reflects the increase in net revenues for all companies when the public infrastructure and services are marginally improved. The second term measures the companies' aggregated improvement in safety following from a marginal increase in the public good, inducing lower expected internal and external accident costs. The authorities face two kinds of policy problems. First, the existence of negative externalities means that the regulator should restrict the companies' incentive to drive for longer periods. Second, there is a need to secure a welfare optimal amount of the public good affecting the companies' profitability and accident risk.

2.3 Uniform driving time restriction

Suppose now that a feasible policy for the regulator is to set a uniform driving time restriction, t, and to decide the size of the investments in the public good affecting the expected profitability of all companies. Assuming the uniform restriction, $t^i = t^j \leq, t$, the welfare is defined by $W = \sum_i(q^i(g)t - p^i(t, g)L^i) - cg$, where we implicitly suppose that all companies are actively restricted by the uniform driving time regulation. Maximizing the welfare with respect to t and g gives the following conditions:[10]

$$\text{(a) } \frac{\partial W}{\partial t} = \sum_i q^i(g) - \sum_i p_t^i(t, g)L^i = 0 \quad \text{and} \quad \text{(b) } \frac{\partial W}{\partial g} = \sum_i(q_g^i t - p_g^i L^i) - c = 0 \qquad (6)$$

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[9] The second-order conditions are here, and throughout the following analyses, dropped from the presentations. However, given our prior presumptions regarding the revenue, probability and cost functions, it is a reasonable assumption that these conditions are satisfied.

[10] As pointed out by one of the journal's referees, this means that the heterogeneity among operating companies is sufficiently limited. It can be shown that if some of the companies have sufficiently low q's and/or high p's and/or high L_I's, resulting in situations where it is optimal to choose the t's below the optimal time restriction, these companies should be removed from the total of N before we sum up in the first equation in (7). Moreover, it also follows that these companies' marginal contribution to welfare w.r.t. g in the second equation should be evaluated for their lower chosen level of t.

Equation (6a) can be written as $\frac{1}{N}\sum_i q^i(g) = \frac{1}{N}\sum_i p_t^i(t,g)L^i$. The left hand side is the average net revenue for the industry, which is equal to the average expected marginal social accident cost. Comparing (6a) with the optimal welfare solution in (5a), (6a) also holds for the optimal case because the marginal net revenue with regard to driving time equals the expected marginal social costs with regard to driving time for each company. However, the conditions related to the case of driving time restriction are less restrictive overall than the N equations following from (5a) above. Equation (6b) is similar to equation in (5b), which is the standard efficiency condition in the case of a pure public good. The difference between the optimal solution and this condition is that the marginal gains and costs in the supply of g are evaluated for different values of t's. In cases of the first best, the evaluations are performed when all companies incorporate in production their specific optimal welfare values of driving time, while in this case, all companies are incorporating the common restricted driving time. In the following, we denote the uniform time restriction solution defined in (6) by the symbols $t = t_D$ and $g = g_D$.

2.4 Uniform taxation of driving times

Before we discuss the uniform taxation of driving times, let us suppose for a moment that the public authorities can introduce company-specific taxes, a^i. It then follows from equations (4) and (5a) that the optimal solution concerning driving times is obtainable by setting the taxes such that $a^i = p_t^i(t^i,g)L_E^i$ is satisfied. These company-specific taxes perfectly internalize the expected external costs. However, such detailed company-specific information is not attainable for the regulator. Hence, the authorities must introduce a common uniform tax, a. Regarding this tax, company i's problem is then to choose t^i that maximizes $\pi^i - at^i$. Thus, the optimal driving time for company i in the case of uniform taxation becomes

$$q^i(g) - a = p_t^i(t^i,g)L_I^i \tag{7}$$

From (7) it follows that the driving time for company i is a function of the tax, a, the supply of public infrastructure and services, g, and the size of the internal loss, L_I^i. Let us denote the optimal driving times in this case as $\hat{t}^i = (a, g, L_I^i)$, where it follows that $\frac{\partial \hat{t}^i}{\partial a} = \hat{t}_a^i = -\frac{1}{p_{tt}^i(t^i,g)L_I^i}$ < 0 and $\frac{\partial \hat{t}^i}{\partial g} = \hat{t}_g^i = -\frac{q_g^i - p_{tg}^i(t,g)L_I^i}{p_{tt}^i(t^i,g)L_I^i}$ < 0. This implies that higher taxes cause a shorter driving period, and higher public supply provides incentives to increase the driving period. The welfare solution can now be found by maximizing W with regard to a and g, taking into account the companies' optimal behavior, defined by (7). Thus, the welfare function now becomes:[11] $W = \sum_i \{\pi^i[\hat{t}^i(a,g;L_I^i),g] - p^i[\hat{t}^i(a,g;L_I^i),g]L_E^i\} - cg$. It follows that optimal welfare must satisfy the following conditions:

(a) $\frac{\partial W}{\partial a} = \sum_i [q^i(g) - p_t^i L^i]\hat{t}_a^i = 0$ and

(b) $\frac{\partial W}{\partial g} = \sum_i \{[q^i(g) - p_t^i L^i]\hat{t}_g^i + q_g^i \hat{t}^i - p_g^i L^i\} - c = 0 \tag{8}$

Using equation (7), (8a) and (8b) leads to $a = \frac{\sum_i p_t^i L_E^i \hat{t}_a^i}{\sum_i \hat{t}_a^i} = \frac{1}{N}\sum_i p_t^i L_E^i + \gamma$ and

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[11]The tax costs for the companies are exactly equal to the tax income for the authorities, and hence, assuming that the authorities do not prefer any particular distribution of welfare, the redistribution does not affect overall welfare.

$$\sum_i (q_g^i \hat{t}^i - p_g^i L^i) + (\gamma - \varepsilon) \sum_i \hat{t}_g^i = c \text{ where } \gamma = \frac{cov(p_t^i L_E^i, \hat{t}_a^i)}{\frac{1}{N}\sum_i \hat{t}_a^i} \text{ and } \varepsilon = \frac{cov(p_t^i L_E^i, \hat{t}_g^i)}{\frac{1}{N}\sum_i \hat{t}_g^i}$$

From (8a) we see that the optimal tax reflects an average of the expected external marginal accident costs among the companies, $p_t^i L_E^i$, weighted by each company's marginal response to tax changes, $\hat{t}_a^i$. Moreover, it is seen that this optimal tax equals the average external marginal accident costs plus a term measuring the correlation between the companies' marginal external costs and their marginal response to the tax changes. If companies causing relatively high external accident costs simultaneously appear to be relatively sensitive to tax changes, this correlation term γ is positive, leading to a tax above the average of the expected external costs. In the opposite case – where higher expected external costs coincide with relatively low tax sensitivity – the correlation term γ is negative, producing an optimal tax below the average expected external costs. In the case where the covariance between the marginal expected external costs with regard to driving time and the marginal impact from an increased tax is zero, i.e. γ=0, it follows that $a = \frac{1}{N}\sum_i p_t^i L_E^i$. This happens when all companies respond identically to a change in taxation, i.e., $\hat{t}_a^i = \hat{t}_a^j$ for all N. When this holds, (6a) and (8a) are concurrent, implying that when designing both the uniform driving time restriction and the uniform tax, the optimal solutions are characterized by balancing the average marginal net revenue and average expected marginal accident costs.

Equation in (8b) also contains both a direct and indirect effect on welfare when *g* is increased. We see that the first and the second term reflect respectively direct marginal welfare gains and direct marginal costs with regard to *g* as in the cases above. The sign of the term, $(\gamma - \varepsilon)\sum_i \hat{t}_g^i$, measuring an indirect marginal welfare effect caused by a marginal increase in *g*, is related to the sign of the covariance commented on above, and the covariance between marginal external costs and the companies' marginal response to changes in public supply. In the case where both γ and ε are zero, this third term is zero, meaning that the (6b) and (8b) are concurrent. In the special case where all companies react equally to marginal variations in the public good, i.e. $\hat{t}_g^i = \hat{t}_g^j$ for all N, it follows that $\varepsilon = 0$. [12]

A simplified illustration is presented in Figure 1, where we consider two companies, i and j. We show and compare the outcome from no regulation, the welfare optimal solution, the case of a uniform time restriction and the case of uniform taxation for a given level of the public good. It is seen that the outcome from no regulation, the case of a uniform driving time restriction and practicing uniform taxation mean welfare losses compared to the first-best solution. The uniform driving time restriction implies that the most efficient company j is too "tightly" restricted while the less efficient company i is too "weakly" restricted, where the efficiency losses are summarized by the grey triangles. On the other hand, a uniform taxation implies that company j is too 'weakly' restricted, while company i is too 'tightly' restricted compared with the first best, where the dark triangles summarized the losses.[13]

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[12] Possible distorted optimal rules for public goods under second-best conditions like those found here are common in transport economics; see for instance Mohring (1970) and Wilson (1983) for optimal pricing and investment rules in the cases of traffic congestion.

[13] The curves in the figure are drawn under the simplifying assumption that p_t^i is constantly increasing. However, as commented on by one of the journal's reviewers, in empirical studies one often finds that the marginal probability with regard to driving time increase strongly after about ten hours driving time.
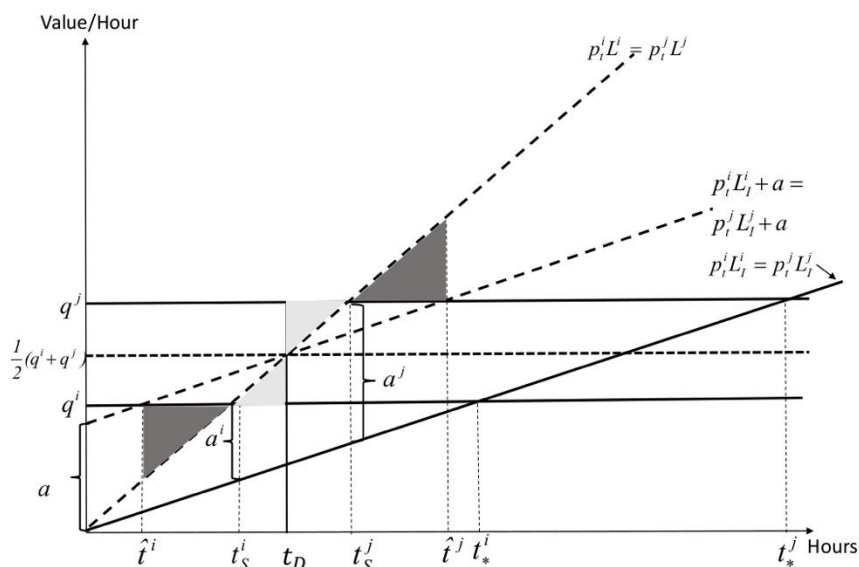
Figure 1.   Optimal driving times for companies i and j when we assume that the two operators differ
only in marginal net revenue, where $q^i < q^j$. The bold upward sloping line is the internal
marginal cost (identical for these two companies), and the steepest dotted curve represents
the expected marginal social cost. The profit maximum solutions, t_*^i and t_*^j, and the welfare
optimal values, t_S^i and t_S^j, are marked on the horizontal axis. The uniform time restriction
solution is t_D, and the total social expected loss stemming from these two firms due to the
uniform time restriction is summarized by the two grey triangles. When a uniform tax, a, is
implemented, the other increasing dotted curve represents the expected internal marginal
costs including taxes, and $\hat{t}^i$ and $\hat{t}^j$ are the companies chosen driving times, and the unique
(optimal) taxes for company i and company j are marked, $a^i < a^j$. The expected social loss
stemming from these two companies due to uniform taxation is summarized by the two
dark triangles.

Based on our model, it is ambiguous whether a uniform driving time restriction or a uniform
taxation is preferred from a welfare point of view. This also holds in the case where $\gamma = \varepsilon = 0$, i.e. that there is no distorted effects from the authorities' choices of tax and public supply
of infrastructure. In this case uniform taxation is socially preferred to uniform driving time
restriction if the sum of the welfare loss from uniform taxation is lower than the welfare loss
in the case of a uniform driving time restriction. This happens if the sum of the two dark
triangles is lower than the sum of the two grey triangles in Figure 1. In the opposite case,
driving time restriction is preferred from a welfare point of view.

3. Enforcement, control and punishment

Turning to the problem of enforcing a driving time restriction, we cease to specify the public
good. The interpretation of this omission might be that the regulator has secured a suitable
amount of the public good before beginning to implement the driving time restriction, or
that different governmental agencies are responsible for the various regulation policies.[14]

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[14] If we had chosen to conduct our analysis of the problem of securing an optimal level of the public good
simultaneously with solving the enforcement problem, similar distorted effects as those commented on in the
uniform taxation case would appear. This implies that the public authorities should be aware of the operators'

3.1 The enforcement regime

To enforce a driving time restriction, $\bar{t}$, let us assume that the public authorities have announced the following fine formula and that the companies are aware of these fines:

$$S = S(t^i - \bar{t}, \alpha) = s(t^i, \alpha) \tag{9}$$

where $S > 0$ and $s_\alpha > 0, s_t > 0, s_{tt} > 0, s_{\alpha t} \geq 0, s_{\alpha\alpha} = 0$ if $t^i > \bar{t}$ and

$S = 0$ and $s_\alpha = s_t = s_{tt} = s_{\alpha\alpha} = s_{\alpha t} = 0$ if $t^i \leq \bar{t}$.[15]

S is the fine if the authority detects company i breaking the driving time restriction, and α is a variable, measuring the penalty level. For all companies that choose driving times less than or equal to the common driving time restriction, there is no penalty. For companies detected breaking the driving time restriction, there will be a positive penalty. Moreover, when the penalty level is increased, the fine becomes higher, $s_\alpha > 0$ and a company breaking the rule faces higher fines as the hours of driving increase, $s_t > 0$, and the growth is intended to increase for higher driving time offences, $s_{tt} > 0$. This formulation of the penalty function is an approximation of current practice.[16] Finally, as higher levels of penalties are applied, the penalty for driving an extra hour might increase, $s_{\alpha t} \geq 0$. Moreover, the public authority uses resources to control the companies' actual driving times. Let r be the probability of detection[17] – the detection probability is assumed to depend the resources allocated by public authorities to detection, e, i.e.,

$$r = r(e) \text{ where } r_e > 0 \text{ and } r_{ee} \leq 0 \tag{10}$$

Higher public effort in detection means a higher probability of finding companies breaking the rule, $r_e > 0$, but possibly at a lower rate as the public effort increases, $r_{ee} \leq 0$.

3.2 Company's adjustments

Let us first consider a company that expects to gain profit by breaking the rules, i.e., $\widetilde{\pi^i} \geq \bar{\pi}^i = q^i\bar{t} - p_t^i(\bar{t})L_I^i$, where $\widetilde{\pi^i}$ denotes the maximum expected profit in the case of breaking the rules, and $\bar{\pi}^i$ denotes profits upon choosing a driving time equal to the driving time restriction. Given the enforcement and penalty regime defined above, the problem of choosing to what degree company i should violate the driving time restriction is solved by maximizing the company's expected profit with regard to driving time, t^i. The expected profit in this case, as in equation (3), is profit minus the expected payment of the fine, defined by rs. Thus, the company maximizes $q^it^i - p^i(t^i)L_I^i - r(e)s(t^i, \alpha)$, implying that the first-order condition becomes

$$q^i - p_t^i(t^i)L_I^i = rs_t \tag{11}$$

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response whether or not to comply with the driving time restriction, and eventually how much they would deviate from the restriction if they do not comply, when the regulator is choosing its level of supply of the public good. Analogously, when designing the optimal enforcement policy, distorted effects on the optimal supply of the public good should be taken into account. Hence, ignoring g here is also a way to simplify the analysis when focusing on the enforcement problem.

[15] It should be noticed that we have chosen to use the symbol $\bar{t}$ for the common driving time restriction when discussing the enforcement problem in order to clarify it from the common driving time restriction, t_D, in section 2.

[16] Here, we suppose that α is measuring the penalty level. Many countries practice a stepwise increasing penalty regime, where the penalty level is stepwise increasing the more the operator deviates from the driving time rule. For instance, the practice in Norway is described in Rundskriv (2000) and Riksadvokaten (2009).

[17] For developments in the probability of detection in Norway, see Elvik and Amundsen (2014).

It is easily seen by comparing equation (4), describing a company's free choice of driving time, with equation (11), that the enforcement and punishment regime as uniform taxation leads to a reduction in driving time, ceteris paribus (see also equation (8a)). Suppose now that $\tilde{t}^i = \tilde{t}^i(e, \alpha)$ denotes the optimal driving time in the case of enforcement. It then follows from (9), the assumptions regarding r and s that in the case of $t^i > \bar{t}$, that $\tilde{t}_e^i = \frac{-r_e s_t}{p_{tt}^i L_I^i + r s_{tt}} < 0$ and $\tilde{t}_\alpha^i = \frac{-r s_{t\alpha}}{p_{tt}^i L_I^i + r s_{tt}} \leq 0$. The first expression above means that when the regulator increases the effort expended in detecting, a company that is initially breaking the driving time rule will want to reduce its driving time violation. Moreover, the second tells us that higher penalty levels mean less driving time violation.

Let us now take a closer look at the incentive to break or comply with the driving time restriction for companies in the industry. Suppose now that we rank the companies, from lowest to highest, in terms of their freely chosen driving time level.[18] For companies where the expected profit stemming from the driving time restriction regime is higher than they could realize by breaking the regulation, these companies choose to comply with the regulation. However, there might be a group of companies who find it profitable to break the driving time restriction. Let company m be the company that is indifferent to either breaking the rule or complying with the regulation, defined as follows: $\bar{\pi}^m = q^m \bar{t} - p_t^m(\bar{t}) L_I^m = \tilde{\pi}^m = q^m \tilde{t}^m - p^m(\tilde{t}^m) L_I^m - r(e)s(\tilde{t}^m, \alpha)$. Differentiation of this equation, using (9), indicates that company m, initially the marginal company, will find it advantageous to comply with the rule if the public effort e increases, the penalty level α rises and/or the driving time restriction $\bar{t}$ becomes higher. Let M be the number of companies complying with and N-M violating the regulation. According to the reasoning above, we have seen that M grows as e, α, and/or $\bar{t}$ are stepped up. We can formulate this behaviour by $M = M(e, \alpha, \bar{t})$, where $M_e > 0$, $M_\alpha > 0$ and $M_{\bar{t}} > 0$.

3.3 Optimal enforcement

Suppose now, to simplify, that the differences among companies are only related to their various net revenues and that the ranking of the companies, based on the q's, can be treated as a continuous distribution. Then, we can formulate the regulator's welfare function as:[19]

$$W = \int_0^{M(e,\alpha,\bar{t})} (q(n)\bar{t} - p(\bar{t})L) dn + \int_{M(e,\alpha,\bar{t})}^N (q(n)\tilde{t}(n,e,\alpha) - p(\tilde{t}(n.e,\alpha))L) dn - he \quad (12)$$

where the first term measures the welfare stemming from the M companies that stick with the driving time restriction, the second term relates to the N-M companies breaking the rule, and the third term is the public cost of enforcing the regulation, where h is the constant cost per unit allocated to detection. The public regulator can adjust the detection effort and the penalty level. We find, using Leibniz's rule, that the first-order conditions become

(a) $\frac{\partial W}{\partial \bar{t}} = M_{\bar{t}}\big(q(m)\bar{t} - p(\bar{t})L - (q(m)\tilde{t} - p(\tilde{t})L)\big) + \int_0^M \big((q(n) - p_t L)\big) dn = 0$

(b) $\frac{\partial W}{\partial \alpha} = M_\alpha\big(q(m)\bar{t} - p(\bar{t})L - (q(m)\tilde{t} - p(\tilde{t})L)\big) + \int_M^N \big((q(n) - p_t L)\tilde{t}_\alpha\big) dn = 0$ (13)

(c) $\frac{\partial W}{\partial e} = M_e\big(q(m)\bar{t} - p(\bar{t})L - (q(m)\tilde{t} - p(\tilde{t})L)\big) + \int_M^N \big((q(n) - p_t L)\tilde{t}_e\big) dn - h = 0$

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[18] We still assume that no firm will choose a lower driving time than that defined by the time limit.

[19] This is slightly different from the welfare functions in section 2 because we have ceased to specify public supply of infrastructure and the costs involved in supplying the public good. As in the case of taxation, we suppose that the authorities are not concerned about the distribution of welfare.

The three conditions in (13) have similarities with conditions we have already deduced in section 2. However, an important difference between the above conditions, in terms of the enforcement problem, and the equation in section 2, are the first terms. These terms measure the increase in the number of companies changing their behavior from breaking the rule to adhering to the driving time restriction, multiplied by the welfare changes these alterations cause for the marginal company as $\bar{t}$, α and e increase. As $M_e > 0$, $M_\alpha > 0$ and $M_{\bar{t}} > 0$, the sign of these terms depends on the sign of $\Delta\bar{w}(m) = q(m)\bar{t} - p(\bar{t})L - (q(m)\tilde{t} - p(\tilde{t})L)$. $\Delta\bar{w}(m)$ which measures the welfare gain when the marginal company changes its behavior from breaking the time restriction to conforming with it. When $\Delta\bar{w}(n) > 0$, welfare is improved if the marginal company turns from breaking the rule to complying with the time restriction. If all these first terms in (13) are positive, it gives the authorities an extra stimulus to increase $\bar{t}$, α and e.

Moreover, in order to see the similarity between the problem of designing an efficient driving time restriction in section 2, ignoring the enforcement problem, and here considering how enforcement might work, let us rewrite (13a) to $\frac{1}{M}\int_0^M q(n)dn = p_t L - \frac{M_{\bar{t}}}{M}\Delta\bar{w}(n)$. We see that the left hand side measures the average marginal net revenue for the companies complying with the rule, while the first term on the right hand side measures the (common) expected marginal social cost for a company. Together, these two terms are similar to what we found in (6a), defining a uniform driving time restriction while ignoring the enforcement problem. However, when considering the enforcement problem, we have a third effect to consider – the second term on the right hand side, measuring the marginal welfare impact from causing changes in the number of companies complying with the rule, and whether their behaving legally or not improves or worsens welfare.

Taking a closer look at (13b), and comparing this with (8a), defining an optimal uniform tax, two important differences are seen. First, when studying the optimal taxation, the marginal impact taxation has on all N companies is relevant, while when analyzing an optimal penalty, the marginal impact is limited to those N - M who break the rule, i.e.

$\sum_i [q^i(g) - p_t^i L^i]\hat{t}_a^i$ versus $\int_M^N ((q(n) - p_t L)\tilde{t}_\alpha)dn$. Additionally, focusing on enforcement also means one has to be aware of the number of companies changing their behavior from breaking the rule to complying with the driving time restricting, and whether such changed behaviour improves welfare or not, measured by $M_\alpha\Delta\bar{w}(n)$.

Finally, let us compare (13c) to (8b). When deciding on an optimal level of a public good affecting productivity and accident probabilities for all companies in the case of taxation, we have seen that both direct and indirect effects on the welfare contribution are relevant, i.e. $\sum_i \{[q^i(g) - p_t^i L^i]\hat{t}_g^i + q_g^i \hat{t}^i - p_g^i L^i\} - c$. To compare, let us write (13c) as

$\int_M^N ((q(n) - p_t L)\tilde{t}_e)dn - h + M_e\Delta\bar{w}(n)$. Although devoting public resources to improving efficiency in transportation and assigning public resources to detection have opposite effects on the companies' incentives when choosing driving times, we see that there are similarities in their indirect effects. Additionally, the regulator has to consider the marginal costs in both activities. When considering increasing g in section 2, the direct effect,

$\sum_i \{q_g^i \hat{t}^i - p_g^i L^i\}$ occurs, while, in the enforcement case, the effect on the number of companies complying with the time restriction and the impact the marginal company has on welfare, $M_e\Delta\bar{w}(n)$, must also be evaluated.

Using penalties to enforce the regulation does not involve any direct costs for the public authorities. However, there might be indirect costs for society when the penalty level becomes too high. To see this phenomenon more clearly, let us further examine companies that initially comply with the rule. For one such company k, it follows from the reasoning above that

$$q^k(\tilde{t}^k - \bar{t}) - (p^k(\tilde{t}^k) - p(\bar{t}))L_I^k \leq rs \tag{14}$$

If the authority is free to choose any level of α, we could conceive of a penalty level high enough to secure a sufficiently large s that all companies would opt to comply with the rules, i.e., M=N. The expression in (14) is thus strictly fulfilled as inequalities. We then have a 'corner solution' to the regulator's problem, implying that the enforcement problem boils down to problem of choosing a sufficiently high level of α so that all companies to find it in their interest to adhere to the driving time restriction. However, in our model, where the companies differ with regard to efficiency, a steadily increasing penalty level will sooner or later force companies with an optimal level of driving time greater the uniform driving time restriction to comply with the rule. Thus, forcing companies with an optimal driving time higher than the uniform driving time restriction to comply with the rule will precipitate welfare losses. Even in a situation where it is possible to establish a penalty level forcing all companies to comply with the rule, this reasoning shows that such a policy does not represent optimal enforcement. Generally, this is a consequence of putting in place a
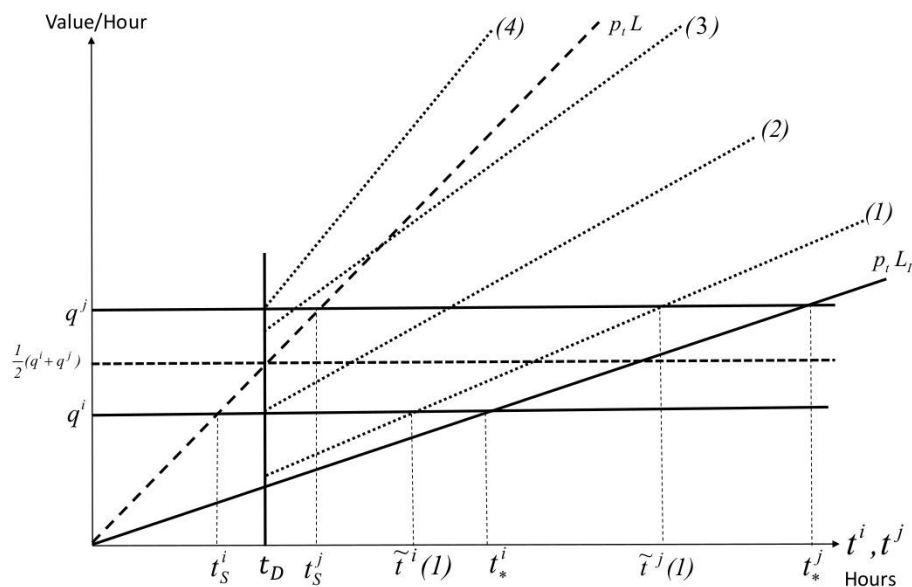

Figure 2.   Consequences of time restriction enforced by various levels of public control effort. We consider two companies that differ only in marginal net revenue ($q^i < q^j$). The dotted curves, marked (1)-(4) illustrate the companies' marginal expected costs (including marginal expected fine payment) for four different levels of control effort ($e^1 < e^2 < e^3 < e^4$, and where we assume that $s_{tt} > 0$). In cases with low level of resources in detection both companies find it advantageous to violate the rule. With a higher level of e, first company complies, and finally, as e is increased, both companies comply with the rule even though this leads to lower driving times than the first best levels.

common time restriction based on the industry average, and thereby releasing the authorities from any obligation to deal with the true variety among the companies with regard to

efficiency and risk. The enforcement problem is exemplified in Figure 2. It shows that the authorities might force companies to comply with a time restriction that is below the companies' first best level, leading to a welfare loss.

Finally, we could think of a situation where the authorities choose penalty levels that are stepwise increasing in the size of the positive deviation from the driving time restriction. In such a case, if the penalty starts on a sufficiently low level, one could possibly see that almost all companies find it advantageously to break the rule marginally, but steadily fewer as the companies face higher penalty levels.

4. Concluding remarks

To the best of our knowledge, this work is the first attempt to discuss public regulations concerning driving time for professional companies conducting road transportation in an economic model. As in many empirical studies of driving behavior, we assume in our model that the probability of accidents and negative events on the roads increase with the hours of driving and that the companies operating on the roads do not bear all costs when accidents occur. Hence, there are negative externalities from road transportation. At the same time, the public authorities are responsible for supplying different types of infrastructure and services to the transport operators both in order to secure efficiency and to prevent accidents. This is because such infrastructure and services affect the transport companies' efficiency and their accident risk level.

4.1 Main results
Our model analyses show that it is necessary for the public authorities to regulate professional transport on the roads both to secure a suitable amount of public infrastructure and services and to ensure that the accident risk do not become excessive. Moreover, even in our simplified model, we have shown that direct regulation – here modelled as introducing a common driving time restriction – has weaknesses regarding its accuracy in securing efficiency. A uniform optimal driving time restriction, defined by the condition that the average marginal revenue equals the average marginal expected accident costs, implies that the most efficient and most secure companies face overly restrictive regulation, while the opposite is true for companies with higher risks and lower efficiency. An optimal designed uniform tax on driving time also lacks accuracy with regard to overall efficiency. We have seen in an example that a uniform tax might encourage the most efficient and least risky companies to choose higher driving times than optimally preferred, while the opposite will occur for the least efficient and most risky companies. In general, it is not possible to decide whether a uniform driving time restriction or a uniform taxation is preferred from a welfare point of view. It depends on the size and the valuation of the deviations from the welfare optimal levels that the different companies experience in these two cases.

To force the industry to account for the externalities arising from their driving behavior, the public authority spends resources to enforce the companies' driving times and introduces penalties for the companies that break the rules. Forcing the most efficient companies to reduce their breaches of the rules might force them to completely comply with the driving time restriction, thus reducing overall welfare. Practically, we know that a substantial number of drivers do break the rules, a fact documented by both authorities' control data and survey data – see for instance Hertz (1991), Braver et al. (1992), Ragnøy and Sagberg

(1999), Nygård (2012, 2014) and Bergland and Gressnes (2014). Such behavior by firms might be welfare optimal, even in a situation where the authorities have designed an optimal enforcement policy. This counterintuitive conclusion follows from the fact that a uniform driving time restriction does not account for the differences between the transport companies with regard to efficiency and probabilities for accidents to happen.

4.2 Implications and possible extensions

Our analyses do not prescribe any easy way to obtain an optimal driving time regulation. Indirect regulation through taxation of driving times has not been practiced in any countries. We believe that such a policy would meet considerable resistance from the companies due to the economic burden taxation would mean for the transport industry. Based on our analyses, a uniform taxation has also weakness due to imposing welfare losses. However, if we had opened our analysis and studied the possibility of practicing more sophisticated taxation schemes, where the tax rate may increase with the hours of driving, it would have been possible to reduce the welfare losses connected to deviations in driving times from the optimal ones. Such non-linear taxes could be implemented and practiced using modern advanced communication systems. However, the same arguments concerning the industry's tax burden would appear.[20]

In order to focus on the design and implementation of driving time regulations, we have simplified the companies' optimal behavior to a single choice of operation time on the roads. In reality the firms choose among several features which affect the capacity and quality of production – for instance the type and size of vehicles and driving speed on the roads. We have also set the driving and resting time regulation as a single uniform restriction referring to maximum driving time and minimum compulsory resting time, both within a day and over several days. The many choices companies make and the time restrictions they have to abide by often lead to complexity in planning efficient routes, see Goel (2010), Prescott-Gagnon et al. (2010) and Goel and Vidal (2014). However, specifying a more realistic and complex time regulation does not introduce any fundamentally new factors regarding the companies' or the authorities' choices, as all these detailed rules actually limit driving time per period.

The vehicle drivers, in addition to the managers and owners of the transportation companies, are able to adjust the actual driving time. We have implicitly assumed that there is no conflict between the managers of the companies and the drivers, which could be the case for smaller transport companies; e.g. if the drivers also are independent business owners/managers as described by Phillips et al. (2015). However, the same authors state that working relationships, working conditions and pay systems vary widely in the different branches of the industry. In a deeper analysis, where the owners and managers act as principals, and the drivers are considered agents, one might encounter conflicting interests regarding the choice of driving time and other operational decisions (for example, speed adjustment). Hence, protecting drivers' working conditions is one of the main objectives of public driving time regulation. In addition, in some situations, the transport demanders – i.e. the customers who buy transport services from the transport companies – may assume the role of the principal. Such conflicting interests and the design of payment contracts may affect the actual choices

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[20]However, in the recent years road pricing has been accepted and implemented by politicians, and the resistance from motorists has been weakened. The same might happen if one introduces driving time taxation.

of driving times and the optimal policy. An interesting discussion on how contracts and public regulation might interact in the heavy-vehicle system can be found in Thompson et al. (2015).

Our analysis assumes that the companies might have different net revenues and that the accident risks and possible internal and external costs involved vary. For instance, such differences mean that a uniform driving time regulation for all companies becomes inefficient, or is a second best solution. Even when companies compete in road transportation markets, variation in productivity among companies, the types of transport missions, and among countries seems a realistic assumption. However, the model reasoning implicitly tells us that the less variation there is, the more efficient a common uniform regulation will be. The enforcement authorities may have some knowledge of the variation among companies and can use such information in determining the control effort within the industry. Moreover, one should be aware that stimulating more efficient competition within the road transportation markets could mean less variation among transport companies, causing the uniform driving time regulation to become more efficient.

The companies' profitability might be affected by stochastic events outside their control, such as weather conditions, traffic flows, closed roads, and network and customer delays. Such unforeseen events result in longer time spent on the roads, and the drivers, following the regulation, might take breaks at unfavorable points in time. Thus, the impact of stochastic events may be magnified by the rules, with detrimental effects for both profit and safety. Hence, many drivers and owners say that they favor more flexible regulation which would ameliorate the impact of these negative events. In two surveys from Northern Europe – Salanne et al. (2013) and Bergland and Gressnes (2014) – drivers report that such unforeseen, delay-causing events, combined with strict driving and resting time restrictions, might reduce the profitability of road transport significantly. Generally, an extended model may address such stochastic variations when designing and implementing driving time regulation. An interesting question in such an analysis is who should bear the risks when stochastic events outside the companies' control shrinks their profitability? In the Arctic regions in the northern part of Norway, for instance, there are few transportation options other than roads. Thus, unforeseen events causing delays, combined with driving time enforcement, might lead to extra costs for both companies and society – see for instance Bardal and Jørgensen (2017).

As mentioned earlier, states within Europe practice the same driving time regulation. Firms that operate in several countries, border crossing transport and simplification have been the most important arguments for the common rules. An interesting question is whether such universal European driving and resting time restriction is preferable to various national regulations, adjusted for local differences in production efficiency, the probability of accidents and external accident costs. Our model discussion shows that if the variations in productivity, accident risks and external accident costs are considerable between countries, a uniform time restriction for all states might lead to inefficiency. However, enforcing and implementing the common driving time restriction is a responsibility of the different national authorities. Hence, in the case of wide variation between countries, the actual enforcement methods chosen by the different countries will vary, which may result in disparate effort and penalty levels, in turn leading to divergent fines and detection functions, i.e., the s-and r-functions in section 3. Thus, a relevant topic for future research on driving and resting time regulations is the modelling of national differences in enforcement in a

situation where there is an overall common driving time regulation. This needs to include the simulation of the shared regulation with more realistic descriptions of functions and parameters in order to assess the detailed and empirical importance on driving time regulation.

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