SUSTAINABLE DEVELOPMENT MECHANISMS FOR A TRANSPORT CORPORATION WITH SUPERVISED LEARNING

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Abstract. Sustainable development of a transport corporation is achieved through a consistent and balanced improvement of its economic and environmental performance indicators. This is largely facilitated by reducing fuel consumption by corporate vehicles, which saves costs and decreases harmful emissions into the environment. In this regard, a three-level structure for managing fuel consumption in a transport corporation is considered under uncertainty caused by both random external factors and the undesirable activity of corporate employees associated with their private goals not coinciding with the goal of the entire corporation. The top level of this structure is the Principal, the middle level is the Intendant, responsible for fuel consumption in a corporate division, and the bottom level is the Driver of a corporate vehicle. The sustainable behavior of corporate employees—the Intendant and Driver—to reduce fuel consumption within their competence is modeled. An organizational mechanism for the Intendant's sustainable behavior is developed, including supervised learning procedures for the Principal and incentive procedures for the Intendant. An organizational mechanism for the Driver's sustainable behavior is also proposed: the Principal provides the Intendant with supervised learning opportunities and delegates his authority to incentivize the Driver. As proven, the integration of these two mechanisms reduces fuel consumption and ensures sustainable development of the transport corporation. In addition, the sustainable behavior of corporate employees—the Intendant and Driver—ensures the sustainability of the entire corporation. The results are illustrated by an example of the fuel consumption management mechanism in JSC Russian Railways.

Keywords: transport, corporation, sustainable development, control, digitalization, supervised learning, sustainable behavior.

INTRODUCTION

Sustainable development is "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. The current global sustainable development goals [2] include:

– efficient use of resources,

– reduction of emissions harmful to human health and the environment,

– establishment of planning and management mechanisms related to climate change.

Among these goals, the creation of cost-saving and environmentally friendly transport systems stands out [2]. Transport accounts for 20–25% of global energy consumption and carbon dioxide emissions [3]. Almost 97% of harmful substance emissions of transport into the atmosphere are gases formed during fuel combustion [4]. They include nitrogen oxides and particulate pollutants, which negatively impact human health [5], as well as carbon oxides and hydrocarbons, which are greenhouse gases [6]. Among all sectors of the economy, the transport industry is characterized by the fastest growth of greenhouse gas emissions [7].

Thus, both efficiency and environmental impact are important for the sustainable development of transport [8]. To achieve global goals, it is necessary for companies to apply sustainable business practices [2]. In this regard, ESG—the concept of sustainable corporate development based on the principles of environmental responsibility (E), social responsibility (S), and effective corporate governance (G)—has become widespread in recent decades [9]. Accordingly, the sustainable development goals of a transport corporation are related to the improvement of its economic and environmental performance indicators by both improving technologies and activating, training, and developing employees; for example, see [10, 11]. The study of the related psychological aspects of sustainable development was initiated in [12]. Further research led to the concept of sustainable behavior [13]. Such behavior implies the employee's understanding of the importance of increasing production efficiency while preserving the environment. The consequence of sustainable behavior is a thrifty attitude to the resources and environment, which brings satisfaction and intrinsic motivation of employees [13].

Note that the vast majority of corporate vehicles (CVs) are equipped with internal combustion engines. These vehicles account for the greater part of the fuel consumption by a corporation. For example, up to 80% of the fuel of JSC Russian Railways is consumed by locomotives with diesel engines (diesel shunters) [10]. Therefore, fuel saving by CVs directly reduces the resource utilization and costs of a corporation as well as its harmful emissions in exhaust gases (including greenhouse gases). On this basis, transport corporations strive to minimize CV fuel consumption by training and activating employees; for example, see [10, 11]. Inculcating employees with the psychology of sustainable behavior helps to conserve CV fuel, thereby reducing both operating costs and pollutant emissions, as well as ensuring compliance with environmental regulations.

Nevertheless, motionless CVs with idling engines are regularly encountered. The point is that in the planning practice of a large transport corporation, the future limits (norms) of fuel consumption by a corporate division and an individual employee are usually lowered when the current fuel consumption decreases. However, the lower the limits (norms) are, the less fuel will be available to a corporate division and an employee to fulfill their tasks. Since fuel consumption depends on random factors, a corporate division and an employee may fail to fulfill these tasks under unfavorable circumstances, with all the ensuing negative consequences. Therefore, a farsighted division manager, as well as an experienced driver, may be uninterested in reducing fuel consumption below the norm. This is a typical problem of adaptive planning from the achieved level, which is studied within the theory of control in organizations [14]. For this kind of problems, a solution approach is to design organizational mechanisms for the operation of corporations [15]. For example, an incentive mechanism to implement environmental requirements for locomotives in JSC Russian Railways was considered in [16].

This paper develops the models of training, activation, and sustainable behavior of the manager and employee of a corporate division, with a focus on reducing the fuel consumption of CVs, and the corresponding organizational mechanisms of sustainable development of a transport corporation.

1. THE SUSTAINABLE BEHAVIOR OF THE INTENDANT

1.1. General Assumptions

Fuel in a corporation is consumed both to meet the needs of CVs (e.g., trucks or diesel shunters) and for miscellaneous demands. These needs and demands depend on random external and internal factors, and many of the latter become known only to a narrow circle of involved persons directly in the course of performing their duties. Assume accordingly that the person responsible for fuel consumption in a corporation (further called the Principal) has inaccurate information about the real possibilities of reducing fuel consumption in his division and CVs. But the Principal can take advice from the Consultant. Both of them get information about the factual fuel consumption of a division. In addition, the Principal can set consumption norms. Based on the deviation of the factual fuel consumption from the norms, the Principal can incentivize the person responsible for fuel consumption in the division (further called the Intendant). However, the Principal cannot determine whether the factual fuel consumption in the division is the minimum achievable in the current conditions.

In view of the aforesaid, we consider a three-level system for managing fuel consumption in a corporation, with a control authority (the Principal) at the top level, a person responsible for fuel consumption in a corporate division (the Intendant) at the middle level, and a CV driver (the Driver) at the bottom level. For this system, it is required to build an organizational mechanism minimizing fuel consumption under uncertainty caused by both random external factors and the undesirable activity of corporate employees (the Intendant and Driver), associated with their private goals not coinciding with the Principal's goal.

We introduce the following notation: t is the time period, $t = 0, 1, \ldots$; d_t is the fuel consumption of the division in period t, consisting of the fuel consumption c_t of the CV and the miscellaneous fuel consumption s_t of the division: $d_t = c_t + s_t$. The value of c_t is reported by the Driver to the Intendant in period t. By assumption, $c_t \in C_t = \left[L(t),\ \gamma\right]$, where

$L(t)$ is a stationary random process determining the realization (value) l_t of the random variable of the minimum CV fuel consumption in period t, $L(t) \in \Lambda = [\delta, \varepsilon]$ with $\delta > 0$ and $\varepsilon \le \gamma$. Hence, $c_t \in \mathrm{C} = [\delta,\ \gamma]$, $t = 0, 1, ...$

The miscellaneous fuel consumption s_t in period t is specified by the Intendant, $s_t \in S_t = [M(t), \alpha]$. Here, $M(t)$ is a stationary random process determining the realization (value) m_t of the random variable of the minimum miscellaneous fuel consumption, $M(t) \in \mathrm{M} = [\mu, \beta]$ with $\mu > 0$ and $\beta \le \alpha$. Hence, $s_t \in \Sigma = [\mu, \alpha]$, $t = 0, 1, ...$

As $d_t = c_t + s_t$, we obtain $d_t \in \Psi_t = [A(t), \alpha + \gamma]$, where $A(t) = L(t) + M(t)$ is a stationary random process determining the realization (value) a_t of the random variable of the minimum fuel consumption by the division, $a_t = l_t + m_t$, $t = 0, 1, \ldots$ It follows from $c_t \in \mathrm{C} = [\delta, \gamma]$ and $s_t \in \Sigma = [\mu, \alpha]$ that $d_t \in \Delta = [\delta + \mu, \alpha + \gamma]$.

Suppose that in period t, the Principal knows the factual fuel consumption d_t of the division. However, he is unaware of the realization (value) a_t of the random variable of the division's minimum fuel consumption. To incentivize the Intendant's fuel consumption reduction under uncertainty, the Principal assigns him one of two categories, namely, 1 (reasonable consumption) and 2 (unreasonable consumption), using the known consumption d_t, $t = 0, 1, \ldots$ This has to be done with minimum losses.

1.2. The Complete and Partial Awareness of the Principal

In this subsection, the Principal is assumed to know, in period t, the realization a_t of the random variable of the minimum fuel consumption of the division, $a_t = l_t + m_t$, $t = 0, 1, \ldots$ This realization is characterized by the dimensionless relative rate $e_t = a_t / (\alpha + \gamma), 0 < e_t \le 1, e_t \in D = [(\delta + \mu)/(\alpha + \gamma), 1]$, $t = 0, 1, \ldots$ The problem is to assign category 1 or 2 to the Intendant by relating e_t to one of two unknown subsets D_1 and D_2 forming the set D: $D_1 \cup D_2 = D$.

Under complete awareness, the Principal knows the rate e_t to belong, with a conditional distribution density $\epsilon(e_t \mid \eta)$ and a prior probability ζ_η, $\eta = \overline{1, 2}$, to one of the two subsets D_1 and D_2, $D_1 \cup D_2 = D$. We denote by q_{12} the losses due to the Principal's erroneous relation of e to the subset D_2 if e actually belongs to the subset D_1. Similarly, q_{21} is the losses due to the Principal's erroneous relation of e to the subset D_1 if e actually belongs to the subset D_2.

We introduce a classification parameter p separating the subsets D_1 and D_2: $e \in D_1 = [(\delta + \mu)/(\alpha + \gamma),\ p]$ if $e \le p$ and $e \in D_2 = (p, 1]$ otherwise. Then the optimal dichotomy $\{D_1, D_2\}$ is determined by solving the following optimization problem over p, with the mean categorization losses as the objective function:

$$\sum_{\eta=1}^{2} \sum_{\theta=1}^{2} q_{\eta\theta} \int_{D_\theta} \zeta_\eta \epsilon(e \mid \eta) de \underset{\{D_1,\ D_2\}}{\rightarrow} \min. \qquad (1)$$

Here, θ is the variable of summation, $\theta = \overline{1, 2}$, and D_θ, $\theta = \overline{1, 2}$, are subsets of D_1 and D_2.

Under partial awareness, the Principal does not know the above probability characteristics. Hence, the value of the parameter p cannot be determined by solving problem (1). However, by observing the random realization a_t, $t = 0, 1, \ldots,$ of the division's minimum fuel consumption, it is possible to obtain and sequentially refine the estimates p_t of the value p, using the supervised learning algorithm with the help of the Consultant [17]. Knowing the fuel consumption rate (e_t), the Consultant reports his opinion $B(e_t)$ to the Principal: the rate is excessive $(B(e_t) = 1)$ or not $(B(e_t) = 0)$:

$$B(e_t) = \begin{cases} 1 \text{ if } e_t > p \\ 0 \text{ if } e_t \le p, \end{cases} \qquad (2)$$
$$t = 0, 1, ...$$

where $B(\cdot)$ is the consulting procedure. Then the Principal can apply the supervised learning algorithm [17]

$$p_{t+1} = P(p_t,\ e_t) = p_t - \iota_t [p_t - 0.5 - q_{12} + (q_{12} + q_{21}) B(e_t)], \qquad (3)$$
$$p_0 = p^0,\ t = 0, 1, ...$$

Where $\iota_t \in \mathrm{I} = \left\{ \iota_t > 0 \mid \iota_t > \iota_{t+1}, \sum_{\sigma=1}^{\infty} \iota_\sigma < \infty \right\}$. If $e_t \le p_t$, the Principal will assign category 1 to the Intendant; otherwise, category 2. Thus, the Intendant's category is given by

$$k_t = G(p_t, e_t) = \begin{cases} 1 \text{ if } e_t \le p_t \\ 2 \text{ if } e_t > p_t, \end{cases} \quad (4)$$
$$t = 0, 1, \ldots$$

1.3. The Unawareness and Supervised Learning of the Principal

Suppose now that the Principal and Consultant are unaware of the above probabilities and the minimum fuel consumption a_t. However, they know the factual fuel consumption d_t. We introduce a relative rate of this consumption: $i_t = d_t / (\alpha + \gamma)$, $0 < i_t \le 1$, $i_t \in D = [(\delta + \mu)/(\alpha + \gamma), 1]$, $i_t \ge e_t$, $t = 0, 1, \ldots$ Then the Consultant determines his opinion using the procedure (2) with the observed rate i_t instead of the unknown e_t. More precisely, having obtained i_t, the Consultant informs the Principal of his opinion $B(i_t)$: the consumption is accurate $(B(i_t) = 1)$ or not $(B(i_t) = 0)$:

$$B(i_t) = \begin{cases} 1 & \text{if } i_t > p \\ 0 & \text{if } i_t \le p, \end{cases} \quad (5)$$
$$t = 0, 1, \ldots$$

Accordingly, the Principal calculates an estimate b_t of the parameter p_t using formula (5), replacing the unknown e_t in algorithm (3) with the observed one i_t:

$$b_{t+1} = P(b_t, i_t) = b_t - \iota_t [b_t - 0.5 - q_{12} + (q_{12} + q_{21}) B(i_t)], \quad (6)$$
$$b_0 = p^0, \ t = 0, 1, \ldots,$$

where $P(\cdot)$ is the learning procedure. By comparing i_t and b_t similar to formula (4), the Principal determines the fuel consumption category g_t of the Intendant's division:

$$g_t = G(b_t, i_t) = \begin{cases} 1 \text{ if } i_t \le b_t \\ 2 \text{ if } i_t > b_t, \end{cases} \quad (7)$$
$$t = 0, 1, \ldots,$$

where $G(\cdot)$ is the categorization procedure. The value of b_t can be interpreted as the normative value of the rate i_t, depending on which the Intendant's category is assigned. Since $i_t = d_t / (\alpha + \gamma)$, the value $h_t = b_t (\alpha + \gamma)$ means the fuel consumption threshold for the division (d_t). If this threshold is not exceeded (i.e., $d_t \le h_t$), the Intendant will receive category 1 $(g_t = 1)$ and an incentive; otherwise, $g_t = 2$ and the Intendant will not be incentivized (or even penalized).

The consulting (5), learning (6), and categorization (7) procedures make up the Principal's organizational mechanism $\Phi = (B, P, G)$ for managing the division's fuel consumption.

1.4. The Intendant's Goals and Decisions under the Principal's Supervised Learning

Using the mechanism $\Phi = (B, P, G)$, the Principal learns with the prompting of the Consultant, assigns a category, and incentivizes the Intendant based on the observation d_t and the calculated rate i_t, $t = 0, 1, \ldots$ However, the Intendant is more aware of the fuel consumption than the Principal and can use this to his advantage. By assumption, at the beginning of period t, the Intendant knows the factual CV fuel consumption c_t and the realization m_t of the random variable of the minimum miscellaneous fuel consumption. The Intendant then selects a value of d_t from the condition $d_t \ge f_t \equiv c_t + m_t$ so that $d_t \in Y_t = [f_t, \beta + \gamma]$ and $f_t \in H = [\delta + \mu, \beta + \gamma]$, $t = 0, 1, \ldots$

Consider how the Intendant makes his decisions under the mechanism $\Phi = (B, P, G)$. A farsighted Intendant seeks to choose d_t in period t to improve both current and future categories. For this purpose, he may control the division's miscellaneous fuel consumption s_t and the CV fuel consumption c_t. Formally, the Intendant chooses d_t by the desire to increase the utility of the categories in period t:

$$T_t = T[g_t, \ g_{t+1}, \ldots, \ g_{t+\lambda}], \quad (8)$$
$$T_t \downarrow g_\nu, \ \nu = \overline{1, \lambda}, \ t = 0, 1, \ldots,$$

where $T[\cdot]$ is a monotonically decreasing function of its arguments (the utility of any category for the Intendant decreases with its number) and λ is the Intendant's foresight.

According to the procedure (7), the category g_t depends only on the Intendant's choice of the fuel consumption d_t, $d_t \in Y_t$. However, to increase the current category utility (8), the Intendant should consider the impact of d_t on the category g_ξ in a future period ξ, $\xi = \overline{t+1, t+\lambda}$. Due to formula (7), this category g_ξ depends on the Intendant's choice d_ξ and the estimate b_ξ in the period. In view of the expression (6), the estimate b_ξ depends on the Intendant's choice d_ω and the estimates b_ω in the previous periods ω, $\omega = \overline{t, \xi-1}$. With formula (6) treated as a recurrence relation, it can be easily established that the category g_ξ depends on the Intendant's previous choices d_ω, $\omega = \overline{t, \xi-1}$.

Note that at the beginning of period ξ, the Intendant will know the realization $f_\xi = c_\xi + m_\xi$, $f_\xi \in H$, $\xi = \overline{t+1, t+\lambda}$. Suppose that the Intendant will also know the future CV fuel consumption c_σ and the miscellaneous fuel consumption m_σ, $\sigma = \overline{\xi+1, t+\lambda}$. Then the Intendant can choose d_ξ by maximizing the objective function (8) with the known realization f_σ, $\sigma = \overline{\xi+1, t+\lambda}$ subject to the condition $d_\xi \in Y_\xi$, $\xi = \overline{t+1, t+\lambda}$. As shown above, the Intendant should consider the impact of d_ξ on the future categories g_σ, $\sigma = \overline{\xi+1, t+\lambda}$.

Repeating this reasoning sequentially from $\xi = t+\lambda$ to $\xi = t+1$, we obtain that it is reasonable for the farsighted Intendant to predict the choice d_ξ backwards. As a result, the objective function (8) is transformed into the predicted category utility

$$T_t^o = T_t^o\left(g_t,\ f_{t+1},..,\ f_{t+\lambda}\right) = \max_{d_{t+1}\in Y_{t+1}} \max_{d_{t+2}\in Y_{t+2}} \ldots \max_{d_{t+\lambda}\in Y_{t+\lambda}} T_t, \tag{9}$$

which depends on the realizations f_ξ, $\xi = \overline{t+1, t+\lambda}$.

However, the Intendant is unaware of the future CV fuel c_ξ and miscellaneous fuel m_ξ consumptions. Therefore, to choose a value of d_t that will increase the predicted category utility (9), the Intendant should predict the fuel consumptions $f_\xi = c_\xi + m_\xi$, $\xi = \overline{t+1, t+\lambda}$. Let the Intendant be guided by the principle of maximum guaranteed result [14, 15], expecting the worst-case predictions $f_\xi \in H$, $\xi = \overline{t+1, t+\lambda}$. Then the function (9) is transformed into the Intendant's objective function

$$\Gamma_t\left(d_t\right) = \min_{f_{t+1}\in H} \max_{d_{t+1}\in Y_{t+1}} \min_{f_{t+2}\in H} \max_{d_{t+2}\in Y_{t+2}} \ldots \min_{f_{t+\lambda}\in H} \max_{d_{t+\lambda}\in Y_{t+\lambda}} T_t. \tag{10}$$

In this case, the set of his optimal choices d_t^* maximizing the objective function (10) in period *t* has the form

$$\Xi_t = \left\{d_t^* \in \Delta \mid \Gamma_t\left(d_t^*\right) \ge \Gamma_t\left(d_t\right), d_t \in \Delta\right\},\quad t = 0, 1, ... \tag{11}$$

Below, we accept the hypothesis of the Intendant's benevolence towards the Principal: if $f_t \in \Xi_t$, then $d_t^* = f_t$, $t = 0, 1, \ldots$ This means that the division consumes more fuel only if it increases the Intendant's objective function (10).

1.5. An Organizational Mechanism for the Sustainable Behavior of the Intendant

The mechanism $\Phi = \left(B, P, G\right)$ is designed to ensure the Intendant's sustainable behavior, aimed at improving both the economic and environmental performance indicators of the corporation. Therefore, such behavior should be expressed in terms of the Intendant's desire to reduce the division's fuel consumption. This is formally reflected as follows.

Definition 1. The Intendant's behavior is sustainable if, for any given CV fuel consumption c_t, the division's fuel consumption is minimal:

$$d_t^* = f_t,\ t = 0, 1, ... \blacklozenge \tag{12}$$

From a practical viewpoint, as already indicated, large corporations often plan fuel consumption from the achieved level. In this case, the future norm of this consumption is reduced when the factual fuel consumption decreases. In the model under consideration, this means that the norm b_{t+1} (the normative value of the rate i_{t+1} in period $t+1$) is reduced when the current fuel consumption rate i_t decreases. However, according to the procedure (6), the lower the norm b_{t+1} is, the smaller value the fuel consumption rate i_{t+1} in period $t+1$, sufficient for the Intendant to receive the highest category, will take. Since $i_{t+1} \ge e_{t+1}$, where e_{t+1} is a random variable, the Intendant may receive a lower category under unfavorable circumstances. Therefore, the farsighted Intendant may be uninterested in reducing the fuel consumption rate i_t below the norm b_t. (He gets the highest category in period *t* for fulfilling this norm.) Thus, a control mechanism is needed to incentivize the Intendant's sustainable behavior.

Proposition 1. *Under the mechanism* $\Phi = \left(B, P, G\right)$, *the Intendant's behavior is sustainable*.

P r o o f. By formula (5), $B\left(i_\xi\right)$ is a non-decreasing function of i_ξ under the mechanism $\Phi = \left(B, P, G\right)$,

$\xi = \overline{t+1,\, t+\lambda}$. Due to formula (6), $b_{\zeta+1}$ does not grow with increasing $B(i_\zeta)$ and, hence, the same property applies to $b_{\zeta+1}$ when increasing i_ζ, $\zeta = \overline{t,\, t+\lambda-1}$. Furthermore, according to the expression (7), $g_\xi = G(b_\xi,\, i_\xi)$ does not grow with increasing b_ξ, $\xi = \overline{t+1,\, t+\lambda}$. It follows from the above considerations that $g_\xi = G(b_\xi,\, i_\xi)$ is a non-decreasing function of i_t, $\xi = \overline{t+1,\, t+\lambda}$.

In addition, by formula (7), $g_t = G(b_t,\, i_t)$ is a non-decreasing function of i_t. Thus, all arguments of the function $T[g_t,\, g_{t+1},...,\, g_{t+\lambda}]$ do not decrease with increasing i_t. Therefore, according to the expression (8), T_t does not grow with increasing i_t for any realizations $c_{t+1},..,\, c_{t+\lambda}$, $m_{t+1},..,\, m_{t+\lambda}$. Then, due to formula (10), the function $\Gamma_t(d_t)$ achieves maximum at the minimum value of i_t. As $i_t = d_t/(\alpha+\gamma)$, the function $\Gamma_t(d_t)$ achieves maximum at the minimum value of d_t. Recalling that $d_t = c_t + s_t$, we obtain $d_t = f_t \in \Xi_t$ by the expression (11). On the other hand, $f_t \in \Xi_t$ implies $d_t^* = f_t$ based on the hypothesis of the Intendant's benevolence towards the Principal. Hence, by definition (12), the Intendant's behavior is sustainable. ♦

Under the mechanism $\Phi = (B,\, P,\, G)$, the division's fuel consumption reduction, first, does not worsen the Intendant's current category (7) and, second, does not tighten the fuel consumption rates in the future. Being benevolent to the Principal, the Intendant minimizes the division's fuel consumption (12).

However, the Intendant's desire to minimize the division's fuel consumption is not enough. In practice, it is common to see motionless CVs with idling engines. To avoid this, the driver of each CV should have a vested interest in minimizing fuel consumption.

2. THE SUSTAINABLE BEHAVIOR OF THE DRIVER

2.1. The Unawareness and Supervised Learning of the Intendant

With the mechanism $\Phi = (B, P, G)$, the Principal ensures the sustainable behavior of the Intendant aimed at minimizing the fuel consumption $f_t = c_t + m_t,\, t = 0, 1,...$ Here, c_t is the fuel consumption of the CV reported by the Driver, $c_t \in C_t = [l_t,\, \gamma]$ (see subsection 1.1). But the Intendant does not know the realization l_t of the minimum CV fuel consumption. The fuel consumption is reduced to the minimum value if $c_t = l_t,\, t = 0, 1,...$

Suppose that the minimum CV fuel consumption (l_t) becomes known to the Intendant at the beginning of period t. Since the Intendant is unaware of l_t, the Driver can manipulate the CV fuel consumption c_t, choosing $c_t > l_t$ if it is profitable for him. On the other hand, the Intendant should minimize the CV fuel consumption $c_t,\, t = 0, 1, \ldots$ To do this, the Principal provides the Intendant with supervised learning capabilities and delegates to the Intendant the right to establish a Driver's operation mechanism similar to $\Phi = (B,\, P,\, G)$. (The Principal uses this mechanism to control the Intendant, see subsection 1.3.)

We introduce the following dimensionless relative rates to measure the CV fuel consumption:

$$k_t = l_t/\gamma,\; K_t = c_t/\gamma,\quad t = 0, 1, \ldots \tag{13}$$

Then the Intendant should reduce the value of the rate K_t to the minimum k_t. Suppose that for this purpose, the Intendant classifies the Driver's performance depending on the CV fuel consumption as satisfactory (class 1) or unsatisfactory (class 0). Incorrect classification incurs costs. To improve the validity of his decisions, the Intendant learns classification with the help of the Estimator, in the same way as the Principal learns categorization with the help of the Consultant (see subsection 1.3).

We denote by ρ_{10} the losses due to the incorrect assignment of class 0 to the Driver (although Driver deserves class 1) and by ρ_{01} the losses due to the incorrect assignment of class 1 to him. The Estimator observes the CV fuel consumption (c_t), calculates K_t by formula (13), and reports his opinion $R(K_t)$ to the Intendant (whether the CV fuel consumption in period t is excessive or not). If the Estimator considers the consumption to be excessive, then $R(K_t) = 1$; otherwise, $R(K_t) = 0$. This is formally written as

$$R(K_t) = \begin{cases} 1 \text{ if } & K_t > \varsigma \\ 0 \text{ if } & K_t \le \varsigma, \end{cases} \tag{14}$$
$$t = 0, 1, \ldots,$$

where $R(\cdot)$ denotes the estimation procedure and ς is the estimation parameter, $\varsigma > 0$. Note that the estimation procedure (14) is similar to the consulting procedure (5). With the considerations of Section 1 repeated, a supervised learning algorithm similar to the procedure (6) can be used to minimize the average classification losses. The tunable classification parameter (briefly, the norm u_τ) is calculated using a recurrence procedure similar to (6):

$$u_{t+1} = U\left(u_t,\, K_t\right) = u_t - \varrho_t\left[u_t - 0.5 - \rho_{01} + \left(\rho_{01} + \rho_{10}\right)R\left(K_t\right)\right], \quad (15)$$
$$u_0 = u^0,\, t = 0, 1, \ldots,$$

where $U\left(u_t, K_t\right)$ is the normalization procedure and $\varrho_t \in \mathrm{P} = \left\{\varrho_t > 0 \mid \varrho_t > \varrho_{t+1},\, \sum_{\sigma=1}^{\infty}\varrho_\sigma < \infty\right\}$, $t = 0, 1, \ldots$ Comparing K_t and u_t, by analogy with the procedure (7), the Intendant determines the Driver's class $\left(v_t\right)$:

$$v_t = V\left(u_t,\, K_t\right) = \begin{cases} 1 \text{ if } K_t \le u_t \\ 0 \text{ if } K_t > u_t, \end{cases} \quad (16)$$
$$t = 0, 1, \ldots,$$

where $V(\cdot)$ is the classification procedure. The value u_t means the norm of the rate K_t used to classify the Driver. Since $K_t = c_t / \gamma$, the value $n_t = \gamma u_t$ can be interpreted as the threshold of the Driver's fuel consumption $\left(c_t\right)$. If this threshold is not exceeded ($c_t \le n_t$), the Driver will receive class 1 $\left(v_t = 1\right)$ and an incentive. The estimation (14), normalization (15), and classification (16) procedures make up the Intendant's organizational mechanism $\Pi = \left(R, U, V\right)$ to manage the Driver's fuel consumption.

2.2. The Goals and Decisions of the Driver Given the Unaware Intendant

Consider how the Driver makes decisions under the mechanism $\Pi = \left(R, U, V\right)$. The norm u_t in this mechanism is interpreted as an upper bound for the CV fuel consumption rate acceptable to the Intendant. If the fuel consumption rate K_t does not exceed the norm $u_t\left(K_t \le u_t\right)$, the Driver will be assigned class 1 ($v_t = 1$) and incentivized. Therefore, the utility of the farsighted Driver increases with current and υ future classes:

$$Z_t = Z\left[v_t,\, v_{t+1}, \ldots,\, v_{t+\upsilon}\right], \quad (17)$$
$$Z_\varphi \uparrow v_\varphi,\ \varphi = \overline{t,\, t+\upsilon},\ t = 0, 1, \ldots$$

According to formulas (13)–(16), the utility (17) depends on the CV fuel consumption c_φ in period φ, $\varphi = \overline{t,\, t+\upsilon}$. In this case, the Driver knows the current realization of the random variable l_t but not the future realizations l_χ, $\chi = \overline{t+1,\, t+\upsilon}$.

Suppose that the Driver is aware only of the inclusions $l_\chi \in \Lambda$ and $c_\chi \in C_\chi$, $\chi = \overline{t+1,\, t+\upsilon}$. When eliminating the uncertainty regarding l_χ and c_χ, $\chi = \overline{t+1,\, t+\upsilon}$, the Driver is guided by the principle of maximum guaranteed result [14, 15]. By repeating the considerations of Section 1, we establish that the objective function $\Theta_t\left(c_t\right)$ of the farsighted Driver is equal to the maximum guaranteed utility (17):

$$\Theta_t\left(c_t\right) = \min_{l_{t+1}\in\Lambda}\ \max_{c_{t+1}\in C_{t+1}}\ \min_{l_{t+2}\in\Lambda}\ \max_{c_{t+2}\in C_{t+2}} \ldots \min_{l_{t+\lambda}\in\Lambda}\ \max_{c_{t+\lambda}\in C_{t+\upsilon}} Z_t. \quad (18)$$

Accordingly, in period t, the set of rates c_t^* maximizing the objective function (18) is

$$\Omega_t = \{c_t^* \in C_t \mid \Theta_t\left(c_t^*\right) \ge \Theta_t\left(c_t\right), c_t \in C_t\}, \quad (19)$$
$$t = 0, 1, \ldots$$

Let us accept the hypothesis of the Driver's benevolence to the Intendant: if $c_t \in \Omega_t$, then $c_t^* = l_t$, $t = 0, 1, \ldots$ This means that the CV consumes more fuel only when increasing the Driver's objective function (18).

2.3. An Organizational Mechanism for the Sustainable Behavior of the Driver

The Intendant's goal is to reduce the fuel consumption c_t to the minimum l_t. This can be prevented by the Intendant's planning from the achieved level (see the discussion above). In the case under consideration, this means that the norm u_{t+1} is reduced as the fuel consumption rate K_t decreases. However, according to formula (16), the lower the norm u_{t+1} is, the less fuel the Driver should consume to obtain class 1 in period $t+1$ ($v_{t+1} = 1$). Since $K_{t+1} \ge k_{t+1}$, and the minimum possible fuel consumption value k_{t+1} is a random variable, under unfavorable circumstances the Driver may obtain class 0 ($v_{t+1} = 0$). For these reasons, the farsighted Driver may be uninterested in reducing the fuel consumption rate K_t below the norm u_t.

Definition 2. The Driver's behavior is sustainable if the CV fuel consumption in each period is minimal:

$$c_t^* = l_t,\ t = 0, 1, \ldots \blacklozenge \quad (20)$$

Proposition 2. *Under the mechanism* $\Pi = \left(R, U, V\right)$, *the Driver's behavior is sustainable.*

P r o o f. With the mechanism $\Pi = \left(R, U, V\right)$ and the procedure (16), the current class $v_t = V\left(u_t, K_t\right)$ is not reduced with decreasing K_t. Consider the dependence of the future class $v_\varphi = V(u_\varphi, K_\varphi)$, $\varphi = \overline{t+1, t+\upsilon}$, on K_t. According to the expression (14), the estimate $R(K_\varphi)$ in period φ does not grow with decreasing K_φ, $\varphi = \overline{t+1, t+\upsilon}$. Due to formula (15), the norm u_φ is not reduced with decreasing $R(K_{\varphi-1})$. In addition, by the expression (16), the class $v_\varphi = V(u_\varphi, K_\varphi)$ is not reduced with decreasing u_φ. Based on the three monotonic dependencies above, the class $v_\varphi = V(u_\varphi, K_\varphi)$ in period φ is not reduced with decreasing K_t for $\varphi = \overline{t+1, t+\upsilon}$.

According to formula (17), the Driver's objective function (18) increases with the growth of the current and future classes v_φ, $\varphi = \overline{t, t+\upsilon}$. From the considerations of the previous paragraph it follows that this objective function $\Theta_t(K_t)$ does not decrease with decreasing K_t. On the other hand, as $K_t \geq k_t$, we obtain $\Theta_t(k_t) \geq \Theta_t(K_t)$, $K_t \in \mathrm{K}_t$, and, by definition (19), $k_t \in \Omega_t$. Hence, based on the Driver's benevolence hypothesis, $K_t^* = k_t$, and the expression (13) leads to formula (20). ♦

3. SUSTAINABILITY MECHANISMS FOR A TRANSPORT CORPORATION

Definition 3. A transport corporation is sustainable if the fuel consumption of its division (including the CV fuel consumption) in each period is minimal:

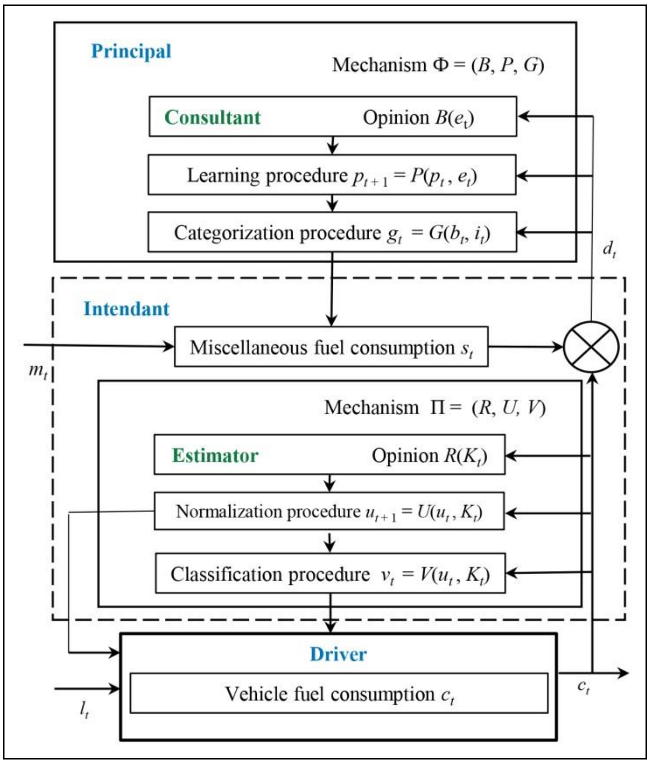
$$d_t^* = a_t,\ t = 0,1,\ldots\ ♦ \tag{21}$$

Proposition 3. *For the sustainability of a transport corporation, it is sufficient to apply the integrated mechanism* $\Sigma = (\Phi, \Pi)$ *consisting of the mechanisms* $\Phi = (B, P, G)$ *and* $\Pi = (R, U, V)$.

P r o o f. Under the mechanism $\Phi = (B, P, G)$, the Intendant's behavior is sustainable (Proposition 1). By Definition 1, this means that for any given CV fuel consumption c_t, the fuel consumption of the division is minimal: $d_t^* = f_t$, $t = 0,1,\ldots$

Under the mechanism $\Pi = (R, U, V)$, the Driver's behavior is sustainable (Proposition 2). By Definition 2, the CV fuel consumption in each period is minimal: $c_t^* = l_t$, $t = 0, 1, \ldots$ Substituting the last equality into formula (12) and using $f_t = c_t + m_t$ and $a_t = l_t + m_t$, we finally arrive at the expression (21). ♦

Actually, the proof of Proposition 3 is based on the fact that the sustainable behavior of the corporate employees (the Intendant and Driver) ensures the sustainability of the entire corporation. Consequently, the integrated mechanism $\Sigma = (\Phi, \Pi)$ can be called the organizational mechanism of the transport corporation's sustainability. The structure of this mechanism is illustrated by the figure below.



The organizational structure and sustainability mechanism of a transport corporation.

4. AN ILLUSTRATIVE EXAMPLE: A SUSTAINABILITY MECHANISM FOR A RAILWAY CORPORATION

Large-scale railway corporations design their own strategies for sustainable (cost-saving and environmentally friendly) development based on the ESG principles; for example, see [10, 11]. To attract passengers and shippers, they need to reduce the fuel consumption of diesel locomotives. This leads to significant cost reductions for interested persons while reducing the environmental load.

Consider such an approach to improving the sustainability of a railway corporation using the example of JSC Russian Railways, further also referred to as the holding. Since about 80% of fuel in the holding is consumed by diesel locomotives [10], they account for about 80% of fuel costs and about 80% of environmental damage due to the emissions of exhaust gases (including greenhouse gases). Therefore, reducing the fuel consumption of diesel locomotives is crucial for the sustainable development of Russian Railways.

Organizational mechanisms for reducing fuel consumption by the holding's locomotives were developed in the paper [18]. These mechanisms include supersized learning procedures for corporate employees [19]. The models and methods for managing the creation and implementation of innovative means and technologies for reducing fuel consumption by the holding's locomotives were presented in the report [10]. These R&D works resulted in a mechanism for reducing fuel consumption that ensures the sustainable development of Russian Railways [10, 18, 19]. The mechanism is an analog of the integrated mechanism presented in the figure.

Consider this integrated mechanism at the regional level. Here, the Principal is an official of the regional railway traction directorate (a branch of Russian Railways) responsible for reducing fuel consumption on the branch's railway network. The Intendant is an employee of the locomotive operation depot (LOD) of this branch responsible for fuel consumption (in short, the manager), and the Driver is a diesel locomotive motorman assigned to the LOD. The responsible persons mentioned are assisted by advisors (as a rule, appointed from former responsible persons).

As a CV we take TEM18DM, a shunting diesel locomotive manufactured by Bryansk Machine Building Plant, a division of CJSC Transmashholding (hereinafter briefly referred to as a/the shunter) [20]. About two hundred shunters of this brand operate on the Oktyabrskaya Railway. Consider the organizational mechanism $\Pi = (R, U, V)$ as applied to the interaction between the manager and driver in the LOD of the Oktyabrskaya Railway when operating a shunter (e.g., in the "Saint Petersburg–Finlandsky" LOD [20]).

According to Proposition 2, under the mechanism $\Pi = (R, U, V)$, the motorman's behavior (as the Driver) is sustainable. Therefore, to reduce fuel consumption, it is sufficient for the LOD manager (as the Intendant) to apply this mechanism, e.g., during the weekly control of fuel consumption in the LOD. Assume that the motorman reports to the manager the average hourly fuel consumption of his shunter over the last week. We denote by t the week number, $t = 0, 1, ...$ The hourly fuel consumption of TEM18DM (c_t) varies within 10–12 l/h [20]. Therefore, according to subsection 1.1, we set $\delta = 10$, $\gamma = 12$, and $c_t \in \mathrm{C} = [10, 12]$, $t = 0, 1, ...$

Thus, within the mechanism $\Pi = (R, U, V)$, the manager and estimator use the average data on hourly fuel consumption over the previous week (c_t). Following (13), we introduce the dimensionless relative rate of fuel consumption by the shunter: $K_t = c_t / 12$, $5/6 < K_t \le 1$, $t = 0, 1, \ldots$ Next, according to formula (14), the estimator informs the manager of his opinion $R(K_t)$: $R(K_t) = 1$ if the consumption is excessive or $R(K_t) = 0$ otherwise. The manager then calculates the fuel consumption norm u_t of the shunter using the procedure (15). Finally, the manager determines the motorman's class v_t by the procedure (16).

The estimation (14), normalization (15), and classification (16) procedures make up the organizational mechanism $\Pi = (R, U, V)$ used by the manager to reduce the shunter's fuel consumption. To perform model calculations, we suppose that at the end of week t during the subsequent quarter (i.e., $t = \overline{0, 11}$), the motorman reports to the manager the average hourly fuel consumption c_t of his shunter (see the top row of the table). To calculate $R(K_t)$, v_t, u_t by formulas (14)–(16), we take the following parameter values of the mechanism $\Pi = (R, U, V)$: $\varsigma = 0.92 \cong 11/12$, $u_0 = 0.90$, $\rho_{01} = 0.5$, $\rho_{10} = 1$, and $\varrho_t = 1/(t+10)$, $t = \overline{0, 11}$. In this case, formulas (14) and (15) turn into:

$$R(K_t) = \begin{cases} 1 \text{ if } K_t > 0.92 \\ 0 \text{ if } K_t \le 0.92, \end{cases} \quad t = \overline{0, 11}, \tag{22}$$

$$u_{t+1} = \{u_t(t+9) + 1.5[1 - R(K_t)]\} / (t+10), \quad u_0 = 0.9, \ t = \overline{0, 11}. \tag{23}$$

The resulting values of v_t, $R(K_t)$, and u_t calculated by formulas (16), (22), and (23), respectively, for 12 weeks of the quarter ($t = \overline{0, 11}$) are given in the table.

This example illustrates the simplicity and transparency of the organizational mechanism $\Pi = (R, U, V)$ as well as the applicability of the proposition.

Fuel consumption by the shunter and the calculated values of the organizational mechanism for the quarter

t	0	1	2	3	4	5	6	7	8	9	10	11
c_t	10.7	11.1	11.0	11.3	10.9	11.0	11.2	10.8	11.2	10.7	10.6	11.1
K_t	0.89	0.93	0.92	0.94	0.91	0.92	0.93	0.90	0.93	0.89	0.88	0.93
v_t	1	1	0	0	0	0	1	0	0	0	1	1
$R(K_t)$	0	1	0	1	0	0	1	0	1	0	0	1
u_t	0.90	0.96	0.87	0.92	0.85	0.90	0.94	0.88	0.92	0.87	0.90	0.93

To ensure the sustainability of Russian Railways, the requirements for the holding's locomotives in the field of environmental protection were supplemented with this organizational mechanism, including the flexible adjustment of fuel consumption rates and norms for the branch and depot level of the traction management hierarchy, and incentives for the employees engaged.

CONCLUSIONS

To develop sustainably, a transport corporation should reduce both economic costs and environmental damage due to its operations. The fuel economy of corporate vehicles significantly reduces both the operating costs of the corporation and the emission of pollutants into the environment. Therefore, the sustainability of a transport corporation depends on the effectiveness of CV fuel consumption management.

Nevertheless, motionless CVs with idling engines are regularly encountered. To avoid this, a transport corporation should ensure the sustainable behavior of middle managers and drivers that improves its economic and environmental performance indicators.

The integrated mechanism proposed in this paper ensures the sustainable behavior of transport corporation's employees by incentivizing them to reduce fuel consumption. The results were used to develop conceptual environmental protection requirements for locomotives of JSC Russian Railways. It is recommended to apply the results also to the vehicles of automobile and water transport corporations.

Further R&D works in this area can be related to:

– designing sustainable development mechanisms for transport corporations with alternative learning procedures;

– generalizing the results for solving other sustainable development problems;

– implementing the theoretical results in practice.

REFERENCES

1. *Our Common Future: Report of the World Commission on Environment and Development*, New York: United Nations, 1987.
2. *Transforming Our World: the 2030 Agenda for Sustainable Development*, UN General Assembly Resolution A/RES/70/1. New York: United Nations, 2015. URL: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf (Accessed April 17, 2025.)
3. Caille, A., Al-Moneef, M., Castro, F.B., et al., *Transport Technologies and Policy Scenarios to 2050*, London: World Energy Council, 2007. URL: https://web.archive.org/web/20081204051628/http://www.worldenergy.org/publications/809.asp (Accessed April 17, 2025.)
4. *About Transportation & Climate Change: Transportation's Role in Climate Change*, Washington: US Department of Transportation, 2015. URL: https://web.archive.org/web/20151031215015/http://climate.dot.gov/about/transportations-role/overview.html (Accessed April 17, 2025.)
5. Kim, M.-K., Park, D., and Kim, D.Y., Quantification of the Ecological Value of Railroad Development Areas Using Logistic Regression Analysis, *International Journal of Environmental Research and Public Health*, 2021, vol. 18, no. 22, art. no. 11764.
6. Iliev, S., Stanchev, H., and Mitev, E., An Experimental Comparison of Emissions of a Common-Rail Diesel Engine Fueled with Ethanol and Butanol Additives, *AIP Conference Proceedings*, 2023, vol. 2868, art. no. 020018.
7. Metz, B., Davidson, O.R., Bosch, R., et al., Transport and Its Infrastructure, in *Climate Change 2007: Mitigation of Climate Change*, New York: Cambridge University Press, 2007, pp. 323–386. URL: https://www.ipcc.ch/report/ar4/wg3/transport-and-its-infrastructure/ (Accessed April 17, 2025.)
8. Savosina, M.I., Assessment of Effectiveness of Sustainable Transport Development, *World of Transport and Transportation*, 2020, vol. 18, no. 2, pp. 50–66.
9. Pollman, E., The Making and Meaning of ESG, *Harvard Bus. L. Review*, 2024, vol. 14, p. 403.
10. Burkov, V.N., Enaleev, A.K., Strogonov, V.I., et al., Models and Methods for Managing the Development and Implementation of Innovative Energy-Efficient Tools and Technologies in JSC Russian Railways, *Report on RFBR Project no. 17-20-05216*, Moscow: Trapeznikov Institute of Control Sciences RAS, 2018. (In Russian.)
11. Union Pacific: Sustainability. URL: https://www.up.com/aboutup/esg/index.htm (Accessed April 17, 2025.)
12. Corral-Verdugo, V., Frías, M., and García, C., Introduction to the Psychological Dimensions of Sustainability, in *Psychological Approaches to Sustainability*, Corral-Verdugo, V., García, C., and Frías, M., Eds., New York: Nova Science, 2010, pp. 3–18.
13. Tapia-Fonllem, C., Corral-Verdugo, V., and Fraijo-Sing, B., Sustainable Behavior and Quality of Life, in *Handbook of Environmental Psychology and Quality of Life Research*, Fleury-Bahi, G., Pol, E., and Navarro, O., Eds., Cham: Springer, 2017, pp. 265–268.
14. Novikov, D.A., *Theory of Control in Organizations*, New York: Nova Science, 2013.
15. Burkov, V., Kondratiev, V., Korgin, N., and Novikov, D., *Mechanism Design and Management. Mathematical Methods for Smart Organizations*, New York: Nova Science, 2013.
16. Enaleev, A., Comprehensive Assessment and Incentive Mechanism to Implement Environmental Requirements for Locomotives, *Proceedings of the 6th International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency*, Lipetsk, 2024, pp. 804–809.
17. Tsyganov, V., Strategic Adaptive Transport Management, *Proceedings of 2024 17th International Conference on Management of Large-Scale System Development (MLSD)*, Moscow, 2024, pp. 1–5. DOI: 10.1109/MLSD61779.2024.10739611

18. Tsyganov, V.V. and Fedyanin, D.N., Mentoring Mechanisms in Organizational Systems and Increasing Energy Efficiency of Railway Transport, *Herald of the Ural State University of Railway Transport*, 2019, no. 3 (43), pp. 55–66. (In Russian.)

19. Tsyganov, V.V., Basyrov, S.K., and Kovalev, S.M., An Energy Efficiency Learning Mechanism in Digital Railway Transport, *Trudy 8-oi nauchno-tekhnicheskoi konferentsii "Intellektual'nye sistemy upravleniya na zheleznodorozhnom transporte. Komp'yuternoye i matematicheskoye modelirovanie"* (Proceedings of the 8th Scientific and Technical Conference "Intelligent Control Systems in Railway Transport. Computer and Mathematical Modeling"), Moscow, 2019, pp. 185–190. (In Russian.)

20. Genkin, D., New Shunting Locomotives, *Oktyabr'skaya Main Line*. November 28, 2019. URL: https://company.rzd.ru/ru/9401/page/78314?accessible=true&id=182659 (Accessed April 17, 2025.) (In Russian.)

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