Quality Estimation Method of Heavy Vehicle Based on Speed Change

Yi Hu\textsuperscript{1,a}, Yongbing Xu\textsuperscript{2,b}, Li Liu\textsuperscript{3,c} and Bihui Jin\textsuperscript{4}

\textsuperscript{1}Wuhan University of Technology, Wuhan, China
\textsuperscript{2}Shanghai Automobile Gear Works, Shanghai, China
\textsuperscript{3}Wuhan University of Technology, Wuhan, China
\textsuperscript{4}Wuhan Technical College of Communications, Wuhan, China

\textsuperscript{a}68235238@qq.com, \textsuperscript{b}geekautoX@163.com, \textsuperscript{c}1149537985@qq.com

Abstract. The heavy-duty vehicle has a wide range of mass changes from no-load to full-load, which affects the shift control of the heavy-duty vehicle transmission. Therefore, the quality of heavy vehicles needs to be identified. The traditional taxiing method needs to know the road rolling resistance coefficient and air resistance coefficient. Acceleration sensor-based automobile quality identification methods require additional sensors on the car, which increases the cost of the car. In this study, based on the principle of function conversion and vehicle longitudinal dynamics, a method for estimating the mass of a heavy vehicle based on changes in vehicle speed is proposed, in the case of unknown vehicle characteristic parameters. In this study, after calculating the air resistance coefficient of the vehicle by the coasting method when the vehicle is under no load, the rolling resistance coefficient of the vehicle is decoupled based on the functional principle and the least square method during the flat road taxiing phase of the heavy vehicle. Based on this, the vehicle longitudinal dynamics model is established, and the mass of the heavy vehicle is estimated by fitting the vehicle speed with the Newton's global algorithm. The research results show that the algorithm of this research can calculate the rolling resistance coefficient of the vehicle in real-time during the taxiing phase of the vehicle, with a calculation accuracy of more than 97%, and the online real-time estimation of the vehicle quality, with an accuracy of more than 95%. The algorithm of this study provides a new solution for online estimation of heavy vehicle driving quality, and can be used for automatic shift control of heavy vehicles.

1. Introduction
The overall quality of a heavy vehicle depends on the quality of the cargo [1]. From no-load to full-load, the mass change range of heavy vehicles can reach 500% [2]. Through vehicle dynamics on-line identification of the overall vehicle quality of heavy-duty vehicles, real-time adjustment of shifting operations of heavy-duty vehicles can be achieved [3], and shifting smoothness and operational stability can be improved. Vahidi [4] can calculate the mass of the car during the neutral taxi phase by using a parameter adaptive algorithm through the vehicle's neutral taxi experiment under the conditions of known vehicle rolling resistance and air resistance. McIntyre [5] obtained vehicle torque
information from the body CAN, based on the vehicle driving force-driving resistance balance, used adaptive least squares method to estimate vehicle mass and road slope, and used a non-linear estimator to Improve the accuracy of its algorithm.

Acceleration sensors can be used to identify the quality of the entire vehicle without decoupling the ramp resistance. Zheng Xuguang et al. [6] used the vehicle acceleration at the moment of vehicle shift to identify the quality of the car, avoiding the impact of the time-varying and uncertainties of the vehicle's characteristic parameters on the quality of the car. This study proposes a mass estimation method for heavy vehicles based on changes in vehicle speed. By combining the principle of function conversion and the vehicle's longitudinal dynamics, the mass of the vehicle can be identified without the vehicle's characteristic parameters. Firstly, the relationship between the rolling resistance coefficient and the air resistance coefficient of the vehicle and the mass of the vehicle is decoupled based on the functional principle and the least square method during the taxiing phase of the heavy vehicle. The vehicle longitudinal dynamics dynamics model is established, and the mass of the heavy vehicle is estimated by the global Newton fitting optimization algorithm.

2. System Description

The algorithm principle of this research is shown in Figure 1. When the vehicle is idling, first calibrate the air resistance coefficient \( \alpha \) of the vehicle. The wheel speed sensor is used to obtain the vehicle speed information when the vehicle is coasting in neutral. Based on the principle of functional conservation when the vehicle is coasting, a conservation equation for the vehicle's longitudinal driving function is established. Combined with the recursive least squares method, the rolling resistance coefficient term has nothing to do with the car quality. Then use Newton's global optimization algorithm to optimize the vehicle speed when taxiing. The processed vehicle speed is fitted by the vehicle longitudinal dynamics equation to obtain the mass of the heavy vehicle.

The hardware of this research is composed of Hall-type wheel speed sensor, single-chip microcomputer and vehicle controller, as shown in Figure 2. Because heavy vehicles are mostly rear-wheel drive, the wheel speed sensor is installed at the rear wheel of the vehicle. The wheel speed sensor obtains the wheel speed information of the vehicle, converts the vehicle speed information into a vehicle controller through a single-chip computer calculation, and sends the vehicle speed
information to the vehicle controller. The vehicle quality identification algorithm embedded in the vehicle controller calculates the vehicle mass in real time during the driving of the vehicle.

![Figure 2. System structure diagram.](image)

3. Modeling

3.1. Vehicle Dynamic Model Based on Work-Energy Principle

![Figure 3. System working principle.](image)

When a heavy vehicle is taxiing in neutral on a flat road, the effect of the lateral force on the vehicle during driving is not considered, and only the longitudinal force of the vehicle is studied. The principle of functional conservation when heavy vehicles slide on flat roads is shown in Figure 3. It is assumed that the speed at which the vehicle is taxiing in neutral at $s_0$ is $v_0$, and the speed when the vehicle is taxiing to $s_1$ is $v_1$. According to the kinetic energy theorem, the energy conservation relationship when the vehicle is coasting is established as:

$$m \frac{v_1^2 - v_0^2}{2} = \int_{s_0}^{s_1} \left( fmg + \frac{C_DA}{21.15} v^2 \right) ds$$

(1)

Among them, $f$ is the rolling resistance coefficient, and $\frac{C_DA}{21.15} v^2$ is the air resistance $F_w$. Because there is a linear relationship between the rolling resistance coefficient and vehicle speed [7], the rolling resistance coefficient model is established as follows:

$$f = f_0 + f_1 v$$

(2)

In the simplified air resistance, the quadratic coefficient of vehicle speed is $a$, then the air resistance is:
Bring equations (2) and (3) into (1), then:

$$m \frac{v_i^2 - v_0^2}{2} = \int_{t_0}^{t_i} \left( f_0 + f_i v \right) m g d s + a \int_{t_0}^{t_i} v^2 d s$$

(4)

Because there is no corresponding relationship between vehicle speed and vehicle displacement, vehicle speed is a function of time, so the integral of vehicle speed versus displacement in Equation (4) needs to be converted into the integral of vehicle speed versus time. The energy expression of the longitudinal dynamics of the vehicle after finishing is:

$$m \frac{v_i^2 - v_0^2}{2} = \int_{t_0}^{t_i} \left( f_0 + f_i v \right) m g v d t + a \int_{t_0}^{t_i} v^3 d t$$

(5)

3.2. Recursive Least Squares for Rolling Resistance Coefficient

In order to identify the real-time car quality during the driving of heavy vehicles, this requires high real-time characteristics of vehicle characteristic parameters. The rolling resistance coefficient of a vehicle is only affected by the speed change during the driving of the vehicle, and has nothing to do with the quality of the vehicle. First, the least square method [8] is used to identify the rolling resistance coefficient of the vehicle online in real time.

Sort the energy expression of vehicle longitudinal dynamics into the form of the least square method:

$$\begin{cases}
y = \phi^T \theta \\
y = \frac{v_i^2 - v_0^2}{2}
\end{cases}$$

$$\phi^T = \left[ g \int_{t_0}^{t_i} v d t \quad g \int_{t_0}^{t_i} v^2 d t \quad \int_{t_0}^{t_i} v^3 d t \right]$$

$$\theta = \left[ f_0 \quad f_i \quad \frac{a}{m} \right]^T$$

So, get: $f_0, f_i, a = \tau m$.

The minimum cost function is sufficient. The cost function is:

$$V(\tilde{\theta}, n) = \frac{1}{2} \sum_{i=1}^{n} \left( y(i) - \phi^T \left( i \right) \tilde{\theta} \right)^2$$

(7)

The iterative form of the least squares method is:

$$\begin{cases}
\tilde{\theta}(k) = \tilde{\theta}(k-1) + L(k) \left( y(k) - \phi^T(k) \tilde{\theta}(k-1) \right) \\
L(k) = \frac{P(k-1) \phi(k)}{1 + \phi^T(k) P(k-1) \phi(k)} \\
P(k) = \left( I - L(k) \phi^T(k) \right) P(k-1)
\end{cases}$$

(8)
3.3. Vehicle Mass Identification Model

After calculating the coefficients of rolling resistance of the vehicle during coasting, the rolling resistance coefficient of the vehicle is determined. From the calculation result of equation (6), it is known that the model can estimate the relationship between the rolling resistance coefficient of the vehicle and the air resistance coefficient of the vehicle and the quality of the vehicle during the driving of the vehicle. The air resistance coefficient of a car can be calibrated according to the taxi method [9] when the vehicle is not loaded. Based on this, the longitudinal dynamic equation of the vehicle when it is coasting is established:

\[-m \frac{dv}{dt} = (f_0 + f_1v)mg + av^2\]  

Therefore, the model of automobile quality estimation is:

\[- \left[ (f_0 + f_1v)g + \frac{dv}{dt} \right] = \frac{a}{m} v^2\]  

In the automobile quality estimation model of this study, the accuracy of the vehicle speed acquisition affects the accuracy of the quality estimation. The actual vehicle traveling speed needs to be optimized. The quality estimation algorithm of this study is that the vehicle speed drops during the neutral taxiing process. Therefore, the global Newton method [10] can be used to optimize the actual driving speed. The principle of global Newton optimization is shown in Figure 4. The data of the vehicle's coasting speed over time is obtained by the vehicle's coasting. The quadratic function approximation is performed using the first and second derivatives of the vehicle speed at time k as the objective function, and then the minimum point of the quadratic model is used as the new iteration point.

![Figure 4. Schematic diagram of Newton's global method to optimize vehicle speed.](image)

4. Analysis

According to the model in the previous chapter, the algorithm of this research can theoretically realize the real-time online estimation of automobile quality. In order to analyze the accuracy, real-time
performance and effectiveness of the quality identification algorithm, the simulation analysis and experimental verification of the algorithm were performed in this study.

4.1. Simulation Analysis
Simulation analysis is mainly used to analyze the accuracy of the algorithm. In order to be able to compare the recognition accuracy of the car quality, some parameters of the virtual vehicle are first set in Unity3D. The vehicle parameters are shown in Table 1.

| Quality (t) | 31 |
|------------|----|
| Rolling resistance coefficient constant term | 0.01 |
| Rolling resistance coefficient constant term | 0.00056 |
| Coefficient of air resistance | 0.436 |
| Windward area of the car (m²) | 7.5 |

After setting the vehicle parameters in Unity3D, select a straight road. After accelerating the vehicle to a certain initial speed, the vehicle is allowed to coast in neutral, and the speed change of the vehicle in neutral is shown in Figure 5.

![Figure 5](image1.png)

**Figure 5.** Changes in vehicle speed over time when the vehicle is coasting in Unity3D.

It can be seen from Figure 5 that the vehicle starts to coast in neutral at an initial speed of 24.7 m/s. Because of rolling resistance and air resistance and no driving force, when the taxiing reaches 180m to 1.9 m/s, the taxiing ends. Fit the vehicle speed-time image in Figure 5 to obtain the vehicle speed as a function of time when the vehicle is in neutral:

\[ v = 30.8 \tan(-0.00340787t + 0.6766) \]

Substituting equation (12) into the rolling resistance and mass estimation model, the rolling resistance and vehicle mass estimation results obtained are shown in Figures 6 and 7.

![Figure 6](image2.png)

**Figure 6.** Rolling resistance identification results.
Figure 7. Auto quality identification results.

It can be seen from figure 6 that at the initial stage of the taxi of the vehicle, the estimated rolling resistance coefficient constant term \( f_0 \) and the first-order term \( f_1 \) differ greatly from the actual values. At the initial stage of the taxi, the amount of data and calculation accuracy are insufficient. As the amount of data input by the algorithm continues to increase, the algorithm results tend to remain unchanged. The final estimates of \( f_0 \) and \( f_1 \) are 0.0103 and 0.000502, respectively. The estimated error of the rolling resistance coefficient constant term is 3\%, and the estimated error of the rolling resistance coefficient linear term coefficient is 10.4\%. Because the first order of the rolling resistance coefficient is usually in the order of \( 10^{-4} \), the estimated error of 10\% has little effect on the estimation of the actual rolling resistance coefficient, mainly based on the constant term of the rolling resistance coefficient.

As can be seen from Figure 7, the actual mass of the car is 31t. 30s before the start of the algorithm, the car quality estimates fluctuated greatly, and the car quality estimates tended to be flat after 92s. This is because the quality estimation algorithm needs to be performed on the basis of the rolling resistance coefficient estimation algorithm, and the calculation accuracy and calculation time of the rolling resistance have an impact on the quality estimation. Therefore, when there is less data in the current period, the algorithm will fluctuate greatly according to the data recursion. When the amount of data is large enough, the algorithm results tend to remain unchanged. At 180s, the mass is estimated to be 30.65t, which is about 1.1\% of the actual error.

4.2. Test Verification
In order to verify the real-time and effectiveness of the algorithm, a straight section was selected for real vehicle test. The test used a 2.5t Great Wall pickup as the test vehicle because its chassis is the same as that of a commercial vehicle and it is easy to change the quality of the car. The test vehicle is shown in Figure 8.

Figure 8. Test vehicle.
The test was conducted under windless and dry road conditions, and neutral sliding was performed at high and low speeds, respectively.

![Figure 9. High-speed neutral taxi speed over time.](image)

![Figure 10. Mass identification results.](image)

It can be seen from Figure 9 and Figure 10 that the test vehicle started to coast in neutral at 56km/h and ended at 10.3km/h. During the period, the mass identification results changed greatly in the first 22s, and the mass identification results were relatively close to the actual vehicle mass within 22s-50s. From 50s to 57s, it can be found from Figure 9 that the car speed fluctuates slightly, and the identification error is 1.148%. The quality identification results in Figure 10 also fluctuate. After 57s, the quality identification results fluctuated. The preliminary estimate is that the decrease in actual vehicle speed has an impact on the accuracy of quality identification.

Figures 11 and 12 show the changes in vehicle speed over time and the results of mass identification during low-speed neutral taxiing, respectively. Due to the low speed and no driving force, the vehicle dropped from 11km/h to 0km/h in 60s when coasting in low speed. It can be seen from Figure 12 that at low speed, the car quality identification results fluctuate greatly, with an error of 6%.
Figure 11. Low-speed neutral taxi speed over time.

Figure 12. Mass identification results.

5. Conclusion
In this study, the accuracy and real-time performance of the mass estimation method of heavy-duty vehicles during neutral taxiing on flat roads were analyzed through simulation and real vehicle tests. The following conclusions were obtained:

1. Based on the change of vehicle speed when the heavy vehicle is in neutral, this study can calculate the rolling resistance coefficient of the vehicle through functional principles combined with recursive least squares method. The identification error of the constant term of the rolling resistance coefficient is 3%, and the estimated error of the coefficient of the primary term of the rolling resistance coefficient is 10.4%.

2. On the basis of the estimated rolling resistance, the quality estimation algorithm of this study can better identify the quality of the vehicle when the vehicle is coasting at high speed with a recognition accuracy of 98.852%. At low speeds, the vehicle quality estimates fluctuate greatly, and the recognition accuracy is 94%.

References
[1] Kim S, Shin K, Yoo C, et al. Development of algorithms for commercial vehicle mass and road grade estimation. International Journal of Automotive Technology, 2017, 18 (6): 1077-1083.
[2] Luo Peipei, Identification of mass and road slope of heavy hydraulic transmission vehicle. Beijing Institute of Technology, Beijing, 2015.
[3] Li Guangyu, Vehicle quality and road slope identification and their influence on shifting rules of pure electric vehicles, Jilin, Jilin University, 2016.
[4] Vahidi A, Stefanopoulou A, Peng H., Experiments for Online Estimation of Heavy Vehicle’s Mass and Time-Varying Road Grade, In: Dynamic Systems and Control, 2003.
[5] McIntyre M L, Ghotikar T J, Vahidi A, et al. A Two-Stage Lyapunov-Based Estimator for Estimation of Vehicle Mass and Road Grade, IEEE Transactions on Vehicular Technology,
2009, 58 (7): 3177-3185.

[6] Zheng Xuguang, Liu Hui, Wang Song, et al. Quality recognition algorithm for heavy vehicle based on acceleration sensor (commercial vehicle AMT), International Automotive Transmission and Electric Drive Technology Symposium, 2013.

[7] Wang Xuming, Experimental Research on Road Slope Test Method, Agricultural Equipment and Vehicle Engineering, 2015, 53 (2): 6-11.

[8] Rhode S, Gauterin F., Online estimation of vehicle driving resistance parameters with recursive least squares and recursive total least squares, In: Intelligent Vehicles Symposium, 2013.

[9] Liao Genghua, Fu Qiang, Sun Shaoyun, Automobile air drag coefficient skid test method: 2015 China Automotive Engineering Society Annual Conference, Shanghai, China, 2015.

[10] Huang Z H, Sun J., A Smoothing Newton Algorithm for Mathematical Programs with Complementarity Constraints, Journal of Industrial & Management Optimization, 2017, 1 (2): 153-170.