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Project Report

Ensuring Measurement Integrity in Petroleum Logistics: Applying Standardized Methods, Protocols, and Corrections

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Abstract: This report analyzes the different standard methods of quantity measurement, which, when applied in the processes of receiving and transferring fuel quantities, lead to discrepancies and accounting losses. Three main factors contribute to these discrepancies: unavoidable errors of measuring devices (calibration uncertainty ranging from 0.1 to 0.5% at best), systematic errors due to non-applied corrections during transactions, and systematic errors due to different regulations, which result in inconsistent conversion rules applied throughout the entire purchase-production-sales chain. Modeling of air buoyancy effects showed that neglecting buoyancy correction can lead to measurable and economically significant discrepancies, especially in large-scale operations. The mass of light petroleum products can be underestimated by up to 0.15%, potentially resulting in approximately $3 million in annual financial losses for a medium-sized refinery processing 10,000 tonnes per day. These findings underscore the necessity of applying buoyancy corrections for conventional weighing, especially for liquid petroleum products (LPP) measured in open systems. Conversely, for LPG weighed in closed, pressurized containers, a constant correction factor (0.99985) applies, but its economic impact is negligible. Therefore, the study recommends omitting this LPG correction unless contractually required, to streamline processes and reduce complexity. Achieving result comparability throughout the entire petroleum supply chain requires implementing uniform quantity calculation provisions using calibrated instruments and standardized methods under different conditions. This necessitates that all measurement results are traceable to reference conditions (mass in vacuum, volume at +15 °C). The proposed algorithms for oil mass and volume measurement and recalculation highlight the need for unified international regulations and a robust system.

Keywords: buoyancy; commercial transactions; liquefied petroleum products; mass in air; measurement losses; temperature correction factor; volumetric and geometric measurement method

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1. Introduction

The fuel industry is fundamentally dependent on the uniform interpretation and application of mass and volume measurement methods. This uniformity is not only a technical aspect; it is essential to ensure fair transactions and transparent pricing, which in turn promotes trust between companies, regulators, and investors and fosters a stable and reliable market [1]. In essence, accurate metrology is the foundation for economic equilibrium in the oil sector [2]. Research has continuously addressed this need by improving oil metering methods to increase accuracy [3] and by utilizing advanced data analysis to provide better insights into fuel consumption patterns, trends, and optimization opportunities [4]. Referenced articles delineate best practices for accurately determining true volume or mass values in commercial transactions [5], while other researchers emphasize the critical need for conformity assessment [6] and strategies to mitigate erroneous assessments during petroleum product transfer [7]. However, a significant gap remains in the comprehensive analysis of strategies to reduce accounting losses directly attributable to fundamental differences in measurement methods [5,8]. Our study addresses this gap.

In standard fuel quantity acceptance and transfer processes, quantity is evaluated using volumetric, gravimetric, and geometric methods. The constant recalculations between volume and mass, driven by available equipment or software, introduce complexity. Each measurement instrument category possesses distinct and variable error characteristics, and while instruments comply with legal requirements, their inherent accuracy differences, especially between static and dynamic modes (e.g., dynamic mass systems ranging from 0.2 to 2% [9]), create an environment ripe for discrepancies. This variability and the resulting measurement errors directly disrupt the economic symmetry of transactions. Even seemingly small errors, when applied to the large volumes common in the petroleum industry, can create a significant asymmetry where one party experiences a financial gain solely due to measurement inaccuracy, while the other incurs a corresponding loss. To illustrate, consider a company producing 100,000 barrels per day. A seemingly minor 0.1% measurement error translates to 100 barrels. At an oil price of $80 per barrel, this represents a $8000 daily loss. In large-scale transactions involving tankers or pipelines, even small measurement errors can lead to losses of thousands of dollars.

Ongoing efforts across various international organizations on standardization, accreditation, and metrology aim to overcome hurdles and achieve greater consistency in fuel measurement practices [10]. By creating international (ISO) and European (CEN) standards, these organizations work to ensure uniform quality and safety in petroleum processes and products [11]. The International Organization of Legal Metrology (OIML), the European Committee for Standardization (CEN), the European Cooperation in Legal Metrology (WELMEC), and the European Association of National Metrology Institutes (EURAMET) develop and harmonize metrology guidelines. These guidelines cover issues related to the selection and testing of measuring instruments and encompass the assessment of oil and petroleum product quantities using various methods [12]. Specialized international and national institutions, such as the American Society for Testing and Materials (ASTM), the American Petroleum Institute (API), the Energy Institute (EI) in London, the National Measurement Institute of Australia (NMIA), and others, play an important role in this regulation process [13,14]. ASTM is the leading organization working in the oil industry [15]. A practical example of implementing ASTM D1250 in the oil industry is its use in converting the volume of crude oil and petroleum products to standardized conditions [16]. For instance, when a refinery or storage facility measures crude oil at a high ambient temperature, they use ASTM D1250 tables to adjust the observed volume to a standard reference temperature of 60 °F (15.6 °C) [16]. For consistent operations, uniform measurement methods and instruments of consistent accuracy must be applied, along with unified metrological supervision. However, while the application of standardized measurement methods and instruments is vital, it does not inherently resolve the challenge of method selection and application across the entire supply chain, especially in individual stages of oil purchase and sale, where methods may differ based on operational needs.

The implementation of international, national standards is not mandatory until it falls within national legal acts (cited standards, standard identification number, name provided) or international agreements are signed for their implementation [17,18].

Despite ongoing efforts by international standardization organizations and specialized bodies to harmonize metrology guidelines, national legislation often lacks consistent [19], clear requirements for mass in air or vacuum, as well as clear guidelines for conversion of calculations and presentation of results when using different measurement principles [20,21].

In Europe, the standard pressure and temperature reference conditions for measuring petroleum products, oils, greases, and gases are 101.325 kPa and 15 °C [22–24]. In Canada and Australia, however, different standard pressures may be used when measuring petroleum products [25,26]. Norway sets the accuracy with which mass or volume must be measured and regulates when corrections must be made; for instance, a correction is required if the deviation exceeds 0.02% of the total volume [27]. Legal requirements for expressing measurement results aren't always consistent or logically justified. For example, accounting rules [28] might demand converting liquefied petroleum gas (LPG) mass to volume at ambient temperature, even when LPG excise duties [29] are based on tonnes. This creates unnecessary recalculations and potential discrepancies. An analysis of measurement result protocols and applicable oil volume regulations at a specific company, conducted during a particular project, revealed an issue: mass isn't consistently converted to volume at ambient temperature, despite this being a requirement of petroleum product accounting rules [30]. These discrepancies can lead to inaccurate inventory management, erroneous financial reporting, and potential regulatory compliance issues.

Regulatory and methodological uncertainty at the national level is also a shortcoming of current practice, preventing full transparency and comparability throughout the oil supply chain.

Figure 1 illustrates a typical, generalized oil processing workflow for a medium-sized regional oil refinery. In Stage 1, the raw material is received through pipelines (where mass is determined using a volumetric method) as well as via rail and trucks (where mass is weighed, and volume is not calculated). Stage 2 involves processing activities, resulting in the production of fuel oil, diesel, LPG, and bitumen, which are then stored in tanks. The internal processes within Stage 2 use the volumetric method to measure volume. Some measuring instruments provide volume measurements, while others quantify in kilograms or tonnes (with a summary provided in tonnes). In Stage 3, petroleum products, LPG, and bitumen are sold by weight, which is determined through weighing. The volume of light petroleum is measured and then converted into mass for final sale and transport in tank trucks. As evident from this workflow, various measurement methods and expressions of quantity are employed. Therefore, it is crucial for all involved parties to reach a consensus on the measurement of quantity, submission of results, and the conversion between mass and volume.

This report aims to ensure consistent mass and volume measurement and conversion in oil refining processes. We'll achieve this by conducting a comparative analysis of standardized weighing, volumetric, and geometric measurement methods used in these operations. To reach our goal, we'll identify the need to assess instrument corrections, including those for buoyancy, temperature, and other factors dependent on the instrument, method, and measurement conditions. To this end, we'll develop consistent algorithms for evaluating results and provide proposals for expressing them, thereby ensuring comparability of results throughout the oil supply chain. Through situational modeling, we'll identify loss reduction trends and offer recommendations for minimizing losses. The analysis of these methods will be linked to measuring instruments and systems employed in oil refining processes, as well as to materials of various densities, including:

- LPP (such as gasoline, diesel, kerosene, etc.) is widely used as fuel in vehicles, industry, and heating.
- LPG, primarily composed of propane and butane, is used as fuel for cars, residential heating, cooking, and industrial applications.
- Liquid-phase bitumen, a viscous, black, and sticky material derived from oil refining, is widely used in road construction, roofing, and waterproofing.

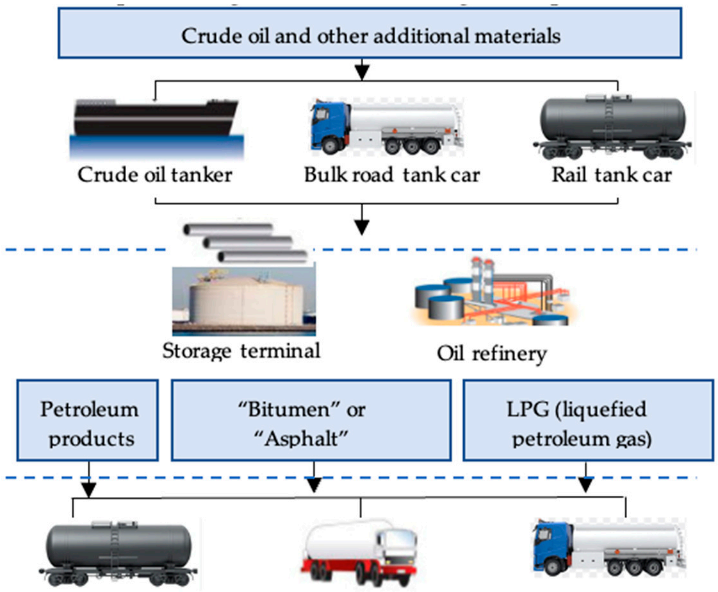


Figure 1. An example crude oil processing workflow.

This report focuses on single transfers between distinct loading/unloading points, not on repeated measurements, mass monitoring, or complex flow system analyses that would involve indirect measurements. We believe that the single measurement result is most influenced by the equipment used and its errors. Other systematic errors due to environmental conditions must be managed.

2. Principles of Mass and Volume Evaluation in the Petroleum Industry

Physical principles of volume and mass estimation are presented in Figure 2. The fundamental physical principles governing volume and mass estimation are as follows:

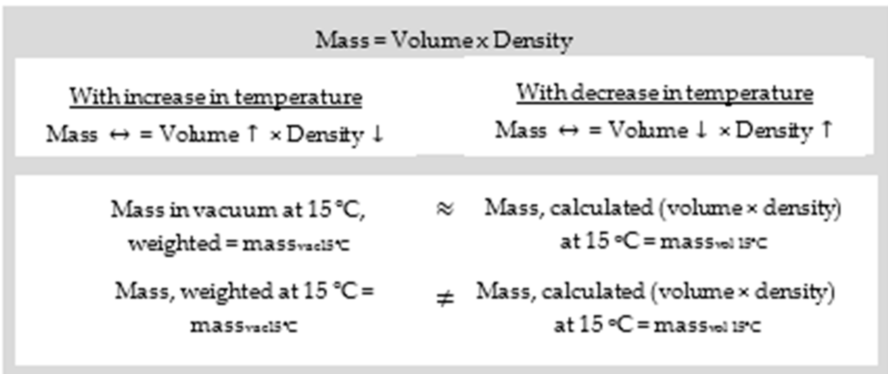


Figure 2. Physical principles of volume and mass evaluation [31].

- Temperature dependence: Mass remains invariant with temperature variations, while volume and density are subject to change. Specifically, an elevation in temperature typically results in an increase in volume and a decrease in density; conversely, a reduction in temperature leads to a decrease in volume and an increase in density. Critically, the intrinsic mass of the substance remains constant throughout these temperature-induced fluctuations.

- Mass measurement in vacuum: The mass of a substance measured in vacuum at a given temperature can be approximated by calculating the product of its volume and density at that temperature. The main reason for any discrepancy between this calculated mass and the measured mass is the accuracy of the instruments used in each measurement method.

To compare quantities measured under different conditions (temperature, pressure, and density), these factors must be corrected for the reference temperature (15 °C, 15.6 °C, and 20 °C) according to the requirements of international standardization and the oil industry, as well as national legislation, with reference to ASTM D1250 [16].

Generally, the following methods are employed to estimate product quantity:

- The weighing method, considered the primary (direct) mass determination method, is the most utilized [9,32]. The method is preferred when high accuracy is essential. Weighing instruments directly measure apparent mass.
- The volumetric method is considered a secondary, indirect method [12]. This method employs various meters and volume measures. Mass is evaluated indirectly. Typically, the volumetric flow rate or total volume of a liquid passing through devices, along with temperature and density, is measured and then converted to a mass value.
- The geometric volume measurement allows for the indirect determination of mass, particularly when fill level, tank geometric parameters, fluid temperature, and density are known. This method is recommended for the calibration, verification, or volume measurement of liquid products in underground or aboveground, horizontal or vertical storage tanks [33–37], as it enables accurate and consistent volume determination without direct weighing. This approach is especially advantageous for large storage tanks where direct mass measurement is impractical.

Principles for the Loading and Unloading of Raw Materials and Products: Measurement Peculiarities Within the Company

Raw material or product quantities are measured using three commonly employed methods, as detailed in Table 1.

Using the weighing method, the gross mass (vehicle and fuel) and the empty vehicle mass are measured. The net mass is calculated as the difference between the full and empty container weights. The fuel mass is then expressed in metric tonnes (in air and vacuum) and recorded in the weighing programs of railway and road tankers, including weighing reports and acceptance documents (acceptance certificates). Measuring instruments used in dynamic and static modes are detailed in Table 2, where d represents the scale division value, **e** the verification scale division value, and Max the maximum weighing capacity.

Volume flow measured by meters is multiplied by density and a volumetric temperature coefficient to calculate mass. For the implementation of this method, the measuring instruments employed for the determination of volume, density, and temperature are presented in Table 3.

Table 1. Methods used and corrections made: mass, volumetric, and geometric methods.

Methods	Materials	Method Implementation	Corrections Applied
Weighing	LPP	The product is weighed in tanks and wagons. Definitions used for weighing instruments: Net weight is an amount of unloaded/loaded product. Gross weight is a total weight of loaded product with the wagon.	Buoyancy correction can be applied (multiplied by a coefficient, and product density is estimated at a reference temperature of 15 °C) or not. Mass-to-volume conversions are possible or impossible.
	LPG	Liquefied gas is weighed in a closed, sealed pressure vessel/tank. Weighing is carried out at factual temperature.	
	Liquid-phase bitumen	Liquid bitumen is loaded into tank trucks at a temperature of 140–180 °C. Internal electric heaters, external electric heating cables, and steam heaters maintain the temperature in the tanks. Weighing is carried out at factual temperature.	
Volumetric method	LPP	After passing through the meter, the product flow is measured at the factual temperature. The result is expressed in kilograms (kg) or liters (L) at 15 °C (for petrol and diesel).	Temperature correction is applied; the reference temperature and product density are estimated at 15 °C.
Geometric method	LPP	The volume is measured at the factual temperature. The result is converted to kilograms (kg) at a reference temperature of 15 °C. The following terms are employed at the terminal to determine the quantity of oil received in tanks: Gross—the total weight of the cargo, inclusive of all impurities. Net—the mass of the cargo, excluding water and sediment (particulate matter).	Temperature correction is applied; product density is estimated at a reference temperature 15 °C.

Table 2. Typical weighing instruments and their characteristics.

Measuring Instrument for Mass Determination	Accuracy Class	Max, e and d Values	Typical Scale Quantities (Significant Measurement Range)
Automatic rail weighbridges	III OIML R76-1 [38] 0.5 and 0.2 in motion OIML R106 [9]	(60,000–200,000) kg, d = e = 50 kg	60,000 kg
Non-automatic rail weighbridges	III	(100,000–180,000) kg, d = e = 50 kg	100,000 kg
Road vehicle scales	III	60,000 kg, d = e = 20 kg	20,000 kg

Table 3. Measuring instruments for the volumetric and geometric mass estimation method.

Measuring Instrument for Volume, Density and Temperature Determination	Maximum Permissible Error	Significant Measurement Range
The volumetric mass estimation method		
Rotary chamber volume meter (flow computer converts L/min to L)	±0.3%	(25–125) m^3
Temperature sensor	±0.1 °C	(−30–70) °C
Density meter	±0.5 kg/m^3	(750–850) kg/m^3
The geometric mass estimation method		
Volume measuring tank (the volume is evaluated using a graduated table) or	±0.2%	(0–56,000) m^3
Level meter	±0.5 mm	(0–20) m
Temperature sensor	±0.5 °C	(−20–90) °C
Density meter	0.6 kg/m^3	(0.75–0.95) kg/L

The geometric method is implemented by calculating the volume of a tank based on its geometric parameters. Subsequently, the mass is derived by multiplying the volume by the density and temperature coefficient. The quantity is measured before and after loading the tank, and the difference in quantities is calculated. The following data are recorded: mass (in metric tonnes) in air and vacuum, gross mass (including impurities) and net mass (excluding impurities), US barrels at 60 °F, m^3 at 15 °C and 20 °C, oil density at 15 °C and 20 °C, and oil temperature. The measuring instruments used are presented in Table 3. Oil density is measured using the method described in ASTM D5002-16 [39].

All measuring instruments correspond to the modern, improved-accuracy equipment held by a typical medium-sized fuel processing company today. For further analysis, we assume that all measuring instruments have been verified or calibrated. Their calibration results (systematic error plus uncertainty) comply with the ISO 17025 [40] standard's decision rule, meaning they fall within the permissible error limits specified in Tables 2 and 3.

3. Mass Evaluation of Petroleum Products Using Weighing Methods

During the mass measurement of petroleum products, specifically when weighing them, the terms "mass in vacuum" and "mass in air" are used. When a product is weighed under normal conditions, the weighing process fails to consider that the product displaces air, leading to a measured mass value that is lower than the actual mass (mass in air). This "mass in air," also referred to as conventional mass, is the value indicated by the weighing instrument.

3.1. Mass Measurement of LPP

The mass of LPP and LPG is obtained by weighing them in the tank, whose mass is known. The mass of LPP is calculated as the difference between the filled tank and empty tank masses:

Mass (Gross) = Empty (Tare) mass + Contents mass (Net),

Contents mass (Net) = Mass (Gross) − Empty (Tare) mass or

$$m = m_{\text{gross}} - m_{\text{t}}, \tag{1}$$

where m is the mass of LPP (Net), kg, m_{gross} is the gross mass (weight indicated by the weighing instrument: tare + product), kg, and m_{t} is the empty (Tare) mass, kg.

Because the weighing instrument indicates a value that is proportional to the gravitational force on the object reduced by the buoyancy in air, the instrument's indication in general has to be corrected for the buoyancy effect [41]. The value of this correction depends on the density of the object (petroleum product) and the density of air [42].

When evaluating a product's mass in vacuum value, there is a need to convert the mass of liquid petroleum indicated on a weighing instrument to mass in vacuum, in which case air buoyancy corrections shall be made according to the equation [41]:

$$m_{\mathrm{vac}} = C \cdot m, \tag{2}$$

where m_{vac} is the mass in vacuum value of LPP, kg, and C is the buoyancy correction coefficient. Coefficient C, is given by the equation:

$$C = \frac{1 - \rho_a/\rho_r}{1 - \rho_{\mathrm{v}}/\rho}, \tag{3}$$

where ρ_{a} is the reference density of air value—equal to 1.2 kg/m^3, ρ_r is the reference density of calibration weight—8000 kg/m^3 (according to [41]), ρ_{v} is the density of gas or vapor that is displaced when the container/vessel/tank is filled, ρ is the density of the LPP. Since the density of air (which has a relatively large value of about 1.2 kg/m^3) can change due to pressure, temperature, or humidity, it may be necessary to consider those factors.

When a liquid product is weighed in an open container/vessel/tank, then the gas displaced can be air, and then ρ_{v} will be equal to ρ_{a}, thus Equation (3) can be expressed as:

$$C = \frac{1 - \rho_a/\rho_r}{1 - \rho_a/\rho}. \tag{4}$$

Buoyancy corrections are adjustments made to account for the effect of air buoyancy when measuring the mass of an object in air. These corrections convert the conventional mass indicated by a weighing instrument to the mass in vacuum, where no buoyant force from the air is present. This process compensates for the reduction in weight due to the displacement of air by the object and ensures that the measured mass accurately reflects the object's mass without external buoyant influences.

As mentioned before, product density depends on the temperature. For buoyancy correction, the density of the product at the observed temperature should be used, but usually the density from the product quality certificate, where it is given at +15 °C temperature, is used. To determine the influence of the density dependence on temperature on the result (i.e., mass in vacuum), we assume that the density of petrol ranges from 740 kg/m^3 (at 15 °C) up to 745 kg/m^3 (at 10 °C) [43]. This density change, due to the temperature change of 5 °C, influences the result by only 0.001%. This can be considered an extremely small value. If the density is measured at a factual temperature, it can be corrected to the density at 15 °C using ASTM Tables 53 [44]. According to the OIML G19 [45], the density is defined as the ratio of product mass (mass in vacuum) and its volume. Thus, we consider that the density specified in the certificates (determined by any method) is the density in vacuum. The diagram for direct product mass evaluation by weighing is given in Figure 3.

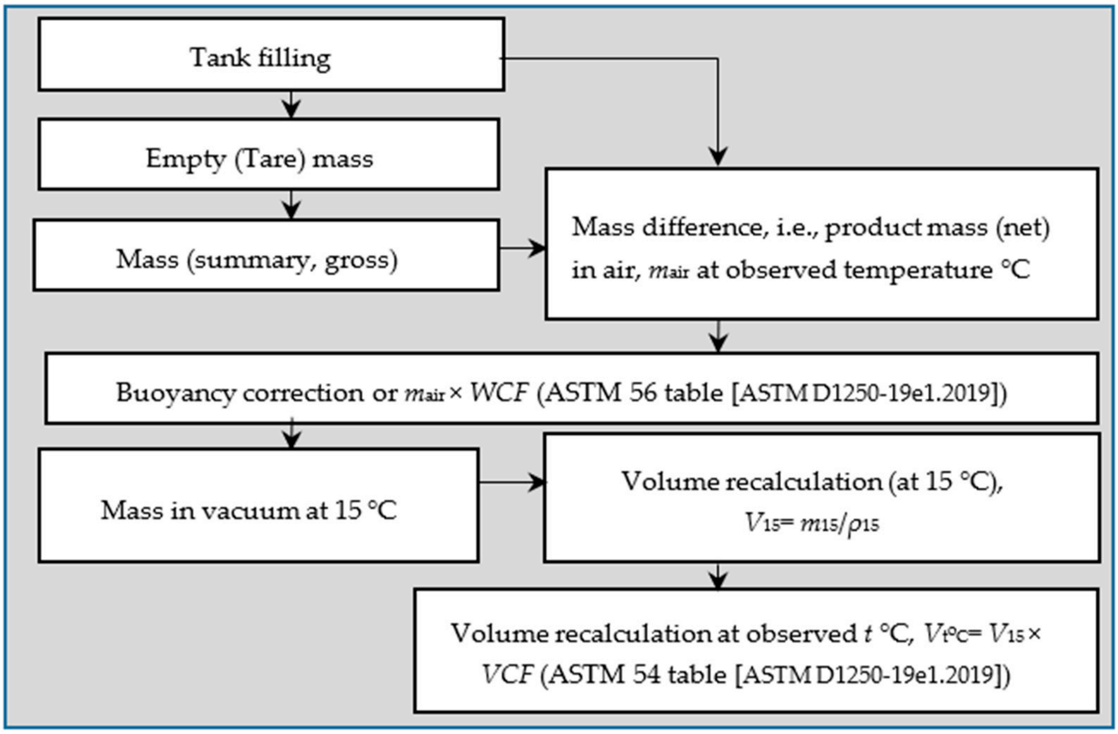


Figure 3. Diagram of LPP mass evaluation (volume recalculation) using weighing method, where m_{air}—product mass (net) in air at observed temperature; *WCF*—weight correction factor; V_{15}—recalculated volume (at 15 °C), m_{15}—product mass at 15 °C; ρ_{15}—product density at 15 °C; $V_{t\,°C}$—recalculated volume at observed temperature; *VCF*—volumetric correction factor; ASTM D1250-19e1.2019—[16].

Considering that mass evaluation is performed using wide-range weighing instruments, let's discuss a scenario where the scale error is e = ±10 kg at approximately 10 tonnes (corresponding to the tare mass of a rail tank car) and e = ±50 kg at 100 tonnes (corresponding to the gross mass of a full fuel rail tank car). Other data used: petroleum product density 740 kg/m^3, air density 1.2 kg/m^3, reference weight density 8000 kg/m. The scenario is chosen according to the significant measurement range presented in Table 2. Using the root sum squared (RSS) method, we can calculate the combined standard uncertainty for the net mass estimation from formula (1).

$$\delta_m = \sqrt{\left(m_{gross}\right)^2 + \left(m_t\right)^2} \approx 54 \text{ kg}. \tag{5}$$

The standard uncertainty for the net mass is approximately 0.1%. The corrected mass in vacuum, where C is 1.00147, is equal to $m_{vac} = 90,132$ kg. The expanded uncertainty is calculated by multiplying the combined standard uncertainty by the coverage factor k, which corresponds to a rectangular distribution with a 95% coverage probability:

$$\frac{\delta_{m_{vac}}}{m_{vac}} = 1.73 \cdot \sqrt{\left(\frac{\delta_m}{m_{vac}}\right)^2} \approx 0.1\ \%. \tag{6}$$

This indicates that the scale error is dominant for the weighing method. The correction does not increase the error; it simply increases the calculated mass in vacuum. As the net mass decreases to 20 t, the standard uncertainty for the net mass increases, and when considering the mass in vacuum, it rises by approximately 4%.

Although the scale error is larger than this specific impact of air density change, the buoyancy correction algorithm removes a fundamental physical influence that consistently affects mass measurements in air. The algorithm allows for the conversion of 'mass in the air' to 'mass in vacuum', regardless of the initial weighing instrument's precision. This process is critical for obtaining an accurate and standardized mass evaluation, which is subsequently used for volume recalculation.

3.2. Mass Measurement of LPG

In the case of LPG, a closed hermetic tank (pressure vessel) is weighed. Measured mass comprises the mass of both liquid product and vapours inside. The resultant mass of LPG is calculated as difference between filled tank and empty tank masses as shown in Equation (1). A closed tank that is filled with LPG has a stable mass despite temperature or liquid and saturated gaseous phase changes [46]. With a temperature change, the liquid gas will expand or contract, and thus the amount of saturated gas in the tank will change; however, the total amount of energy will remain the same. This means that the measured mass will not change. Considering OIML R 125 [47], in a closed tank (e.g., LPG weighing case) ρ_v = 0 as no vapor is displaced. Then, the above-mentioned Equation (2) can be expressed as:

$$m_{vac} = m\frac{1-\left(\frac{1.2}{8000}\right)}{1-\left(\frac{0}{\rho}\right)} = m\frac{0.99985}{1} = 0.99985 \cdot m. \quad (7)$$

A correction factor of 0.99985 is used to estimate the mass of LPG under vacuum in a closed container. The indication of the weighing instrument without correction in this case is the conventional mass [47], which is determined by the characteristics of the weighing instrument and the ambient conditions. Correction coefficient 0.99985 is universal and it does not depend on the type of used weighing instrument, cargo mass, product composition or measurement units. When LPG is weighed, then its amount has to be converted into liters using density $\rho_{15^\circ\mathrm{C}}$, LPG factual temperature T °C and coefficient VCF_T:

$$V_{\mathrm{T}^\circ\mathrm{C}} = \frac{m}{\rho_{15^\circ\mathrm{C}} \cdot VCF_\mathrm{T}}, \quad (8)$$

where $V_{\mathrm{T}^\circ\mathrm{C}}$—LPG volume at factual temperature, m—LPG mass, VCF—LPG volume recalculation, from factual temperature to the +15 °C, coefficient, $\rho_{15^\circ\mathrm{C}}$—LPG density at +15 °C (from LPG quality certificate or measured in laboratory). A diagram of the volumetric correction factor (*VCF)* dependency on change of density and temperature is presented in Figure 4.

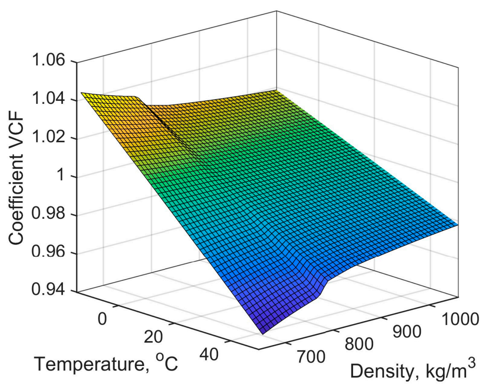


Figure 4. *VCF* coefficient variation dependency on change of density and temperature.

VCF coefficient is equal to the ratio of density at factual temperature and density at reference (+15 °C) temperature $VCF = \frac{\rho_t}{\rho_{15}}$. Its variation is calculated according to

ASTM 54B tables (for petroleum products) [16] and the following conditions: density range 653–1075 kg/m^3; temperature range −15–50 °C.

According to the Figure 4 *VCF* varies with the density of the petroleum product. As density changes (due to product type or composition), the *VCF* adjusts to account for how much the volume shifts under temperature changes. Temperature fluctuations directly impact the *VCF*. As temperature increases or decreases, the VCF changes to reflect the corresponding expansion or contraction of the petroleum product volume. This adjustment is critical for accurate volume measurement, as temperature-induced expansion or contraction can lead to significant variations in perceived volume. Figure 4 thus provides insight into the sensitivity of the VCF to different densities and temperatures, emphasizing the importance of applying accurate VCF adjustments in petroleum measurement to ensure reliable data across varying operational conditions.

3.3. Mass Measurement of Bitumen

The mass of liquid bitumen indicated on a weighing instrument has to be converted to the buoyancy-corrected mass using Equation (2). Buoyancy factor C is calculated using Equation (4). Values of volume correction factor for bitumen mass recalculation to the volume are given in the short table of ASTM D 4311 standard [48].

4. Measurement of Petroleum Product Quantity Using Volumetric and Geometric Volume Measurement Method

When evaluating product mass by volumetric and geometric volume measurement methods, mass is calculated using the results from several direct measurements. Using the volumetric and geometric volume measurement method, mass m of LPP in the tank is calculated using the following equation:

$$m = V \cdot \rho, \tag{9}$$

where V is measured product volume, l, ρ is measured product density, kg/L.

When using the geometric method, the LPP volume in stationary tanks is determined by using level measurements together with the tank graduation tables [31]. For the volumetric method, the meter is used for the volume flow (debit) measurement. In addition, temperature and density are measured, and then mass is calculated [49,50].

A model for mass recalculation that evaluates the influence of volume, density, and temperature is given below [12,51]:

$$m = V\rho(1 + \alpha(t - t_{\mathrm{m}})), \tag{10}$$

where t_{m} is the temperature of LPP, V is product's volume at temperature t_m, ρ is measured product's density at temperature t_m, α is the coefficient of cubical thermal expansion, t is reference temperature. Under the conditions, when the assumed standard temperature is +15 °C, every 5 °C deviation from the standard temperature causes about 0.5% mass change, and respectively, each 10 °C deviation causes—0.95% mass change. This is a significant influence on the measurement result. In all applicable standards and recommendations main temperature correction aspects are discussed [52,53].

Petroleum products quantification stages, using the volumetric/geometric method, are presented in Figure 5. A systematic review of the volumetric/geometric approach is presented here, highlighting the importance of accurate environmental corrections for accurate estimation in the petroleum industry. The main steps of this method are initial volume measurement, temperature and pressure regulation, density determination, and volume-to-mass conversion.

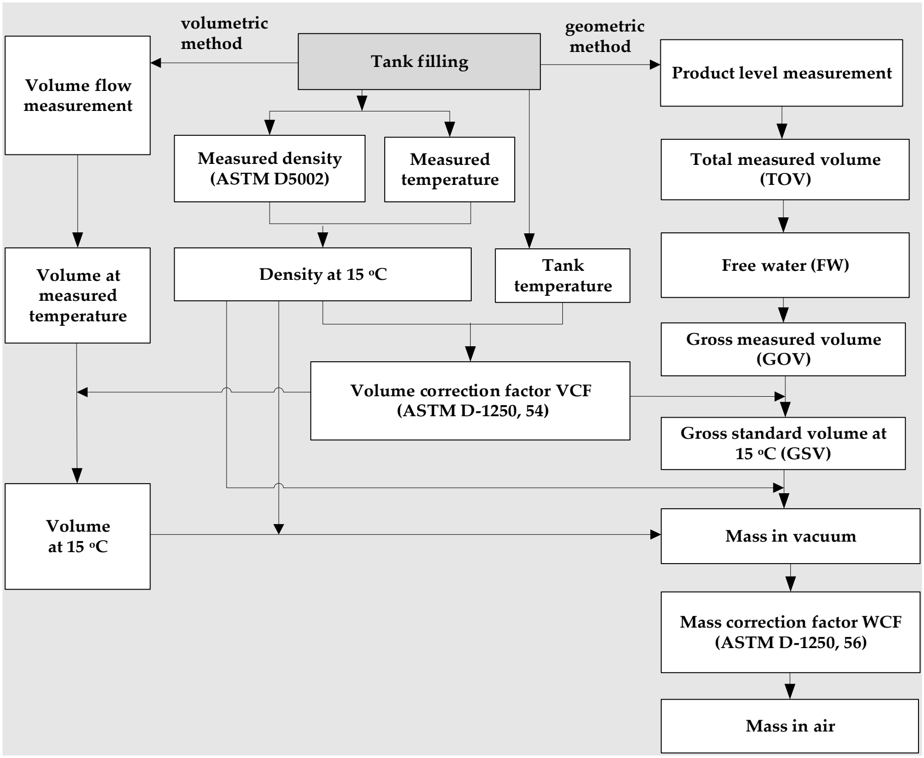


Figure 5. Petroleum products quantification stages, using a volumetric/geometric method, where ASTM D-1250, 54—[16]; ASTM D-1250, 56—[16].

The product volume at 15 °C temperature can be determined according to ASTM Table 54, using tank graduation table and correcting measured temperature to the reference temperature (usually 15 °C). Tank graduation tables are used to convert level measurement (in millimeters) to volume (in liters). Measured product density is also recalculated to the reference temperature. For this purpose, ASTM Table 53 may be used [44].

According to Equation (7), the calculated mass is called the product mass in vacuum. To calculate product mass in air, a weight correction factor (*WCF*) is used, which is selected from ASTM Table 56 [12,54]. The weight correction factor can be calculated if the density in the vacuum and the density in the air are known [31]:

$$WCF = \rho_a = \rho_{vac} - 0.0011, \tag{11}$$

where: ρ_a is product density in air, kg/L, ρ_{vac} is product density in vacuum, kg/L.

Let's consider two methods, volumetric (flow) and geometric, discussing the instruments used, their errors, and the effectiveness of the proposed algorithm. Assume the following instruments and their accuracies are used to implement the volumetric method: the rotary chamber volume meter with an accuracy of ±0.3%; the temperature sensor with an accuracy of ±0.1 °C; and the density meter with an accuracy of ±0.5 kg/m^3 (with a density of 0.820 g/cm^3). The volume range is 25 m^3 to 125 m^3, and the cubical thermal expansion coefficient for petroleum products is 950 × 10^{-6} 1/°C. Applying the root sum squared (RSS) method, we can derive the expanded uncertainty for mass estimation based on formula (10). The expanded uncertainty is calculated by multiplying the combined standard uncertainty by the coverage factor *k* for a rectangular distribution at a 95% confidence level:

$$\frac{\delta_m}{m} = 1.73 \cdot \sqrt{\left(\frac{\delta_v}{V}\right)^2 + \left(\frac{\delta_\rho}{\rho}\right)^2 + (\alpha \cdot \delta t)^2} \approx 0.0053 \approx 0.5\%. \tag{12}$$

In this context, the relative influence coefficients for each constituent are equal to 1, and $\frac{\delta_v}{V} = 0.3\% = 0.003$, $\frac{\delta_\rho}{\rho} = \frac{0.0005}{0.82} = 0.00061$, $\alpha \cdot \delta t = 0.00095 \frac{1}{^\circ C} \cdot 0.1\ ^\circ C$.

The following data is used in the error analysis of the geometric method: the volume measurement error (using the graduation tables) is ±0.2%; the product volume ranges widely from 0 to 56,000 m^3; the temperature sensor accuracy is ±0.5 °C; the density meter accuracy is ±0.6 kg/m^3, with an average density of 850 kg/m^3. The expanded uncertainty for mass estimation using the geometric method is calculated according to formula (12) and is equal to: $\frac{\delta_m}{m} \approx 0.0038 \approx 0.4\ \%$.

Using specific measuring instruments, the volumetric and geometric methods allow for the determination of mass with an expanded uncertainty of less than or equal to 0.5%, which is acceptable by OIML R 117 [55]. Despite the temperature sensor's accuracy, the petroleum product's thermal expansion coefficient of 950×10^{-6} 1/°C means that even relatively small temperature deviations from the reference temperature cause a significant volume/mass change (approximately 0.5% for a 5 °C change). The algorithm effectively manages this correction.

The algorithm consistently converts mass measured in air to a final mass, even when initial measurements are performed with different instruments and under varying environmental conditions. This is crucial for ensuring the accuracy and comparability of reports.

5. Modeling of Existing Processes and Situations. Results and Discussion

5.1. Simulation of Changes in Air Buoyancy Coefficient C

Buoyancy is a force acting on a body that is in a gaseous or liquid medium, directed opposite to the force of gravity, the latter arising due to Earth's gravity. In mass measurements, the effect of buoyancy is equal to the mass of the displaced medium corresponding to the volume occupied by the weighed body. The buoyancy coefficient, provided in formulas (3) and (4), reflects this change in body mass, taking into account the buoyancy of the steel reference weights used during the calibration of scales in the air. The influence of individual components on the buoyancy coefficient C was analyzed through modeling: when weighing oil or oil products in an unsealed container and applying formula (4) for buoyancy evaluation, the effects of air density ρ_a, weight density ρ_r, and the density of the oil product ρ were modeled.

5.1.1. Negligible Effect of Steel Standard Weight Density

Due to a very large difference in the density of steel standard weight and air, the influence of standard weight density, which is assumed to be 8000 kg/m^3 [37,56], is negligible. This assumption is based on a simulated density range of (7000–9000) kg/m^3. Since the influence of this component is negligible and can be ignored, for further simulation, it was constant and equal to 8000 kg/m^3 [57].

5.1.2. Air Density Variability with Temperature, Pressure, and Humidity

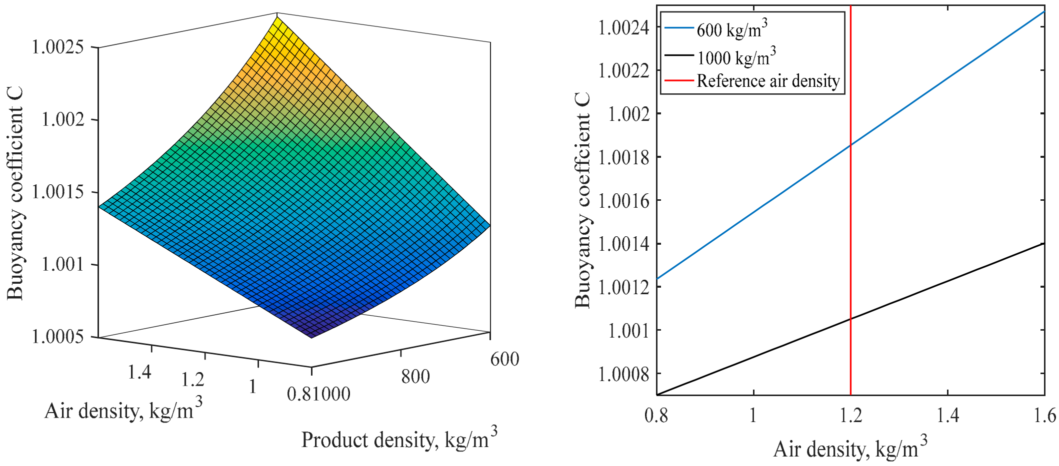
Air density due to temperature, pressure, and relative humidity can vary within the following limits: 0.88 kg/m^3 at 35 °C, pressure 80 kPa, relative air humidity from 100% to 1.50 kg/m^3; at −30 °C, pressure 105 kPa at any relative humidity. The simulation incorporates a range of air densities from 0.8 to 1.6 kg/m^3 to capture these potential variations.

5.1.3. Density Range of Oil and Petroleum Products

Company's production and raw material range determine the density of the oil or petroleum product. During the simulation over the total product density range, which can vary from light oil to heavy oil, the overlap was analyzed for the range of (600–1000) kg/m^3.

5.1.4. Buoyancy Coefficient Dependency on Air and Petroleum Product Density

Figure 6a shows the dependency of the buoyancy coefficient in air on the density of air and petroleum products. Figure 6b shows two sections of this plane.



(**a**) (**b**)

Figure 6. (**a**) Simulation of changes in air buoyancy coefficient *C*, (**b**) Simulation of changes in air buoyancy coefficient *C*: individual cases.

The presented graphs highlight these facts:

1. The dependency of the buoyancy coefficient on air density is linear, whereas this dependency on the density of the product is non-linear.
2. Range of the buoyancy coefficient values is: 1.0007–1.0025 or (0.07–0.25) %.
3. The lighter the product is (i.e., the lower its density) and the higher the density of air, the greater the buoyancy effect.

5.1.5. Maximum Buoyancy Effect

The following conclusion can be drawn when air density is the highest (1.6 kg/m^3, −30 °C, 105 kPa) and petroleum product is the lightest (600 kg/m^3), the maximum buoyancy effect will be 0.25%. Under the real operating conditions, buoyancy correction will be approximately 0.15% (for light oil). Therefore, mass of the product, when m = 100 t is weighed in air, after correction will be: $m_D = m \cdot C_D = 100,000$ kg$\cdot 1.0025 = 100,250$ kg = 100.25 t, $m_R = m \cdot C_R = 100,000$ kg$\cdot 1.0015 = 100,150$ kg $= 100.15$ t, where m_D is the mass value, taking into account the maximum correction for air buoyancy, C_D is the maximum air buoyancy correction coefficient, C_R is the real (typical) correction for air buoyancy, m_R is the mass value when the real (typical) correction for air buoyancy is estimated.

5.2. Analysis of Measurement and Conversion of Quantity at Different Stages of Purchase-Production-Sale

5.2.1. Mass Discrepancies in Air Versus Vacuum Conditions

Assuming a constant air density of 1.2 kg/m^3, buoyancy correction decreases as the density of the product increases. This means that the difference between the same mass in air and in a vacuum is smaller. If the change in mass for light oil is 0.15%, at a density of 1000 kg/m^3 and higher, the change in mass is 0.1% or smaller. These changes, resulting from the introduction of buoyancy corrections, can be regarded as significant in the same order of magnitude as the errors of the measuring instruments used (0.1–0.5)%. Correcting for these variations is essential in reporting and financial transactions to prevent unintended discrepancies.

5.2.2. Economic Implications of Buoyancy Corrections in Petroleum Sales

When calculating mass without buoyancy adjustments, the resulting mass in air is lower than the mass in a vacuum, leading to potential financial losses for suppliers. This discrepancy implies that sellers may be transferring more product weight than is compensated for, particularly in large-scale transactions.

Figure 7 shows the dependency of mass change on production volumes. For the simulation, products of different densities were selected, namely light oil, heavy oil, and bitumen, with densities of 600 kg/m^3, 1000 kg/m^3, and 1500 kg/m^3, respectively.

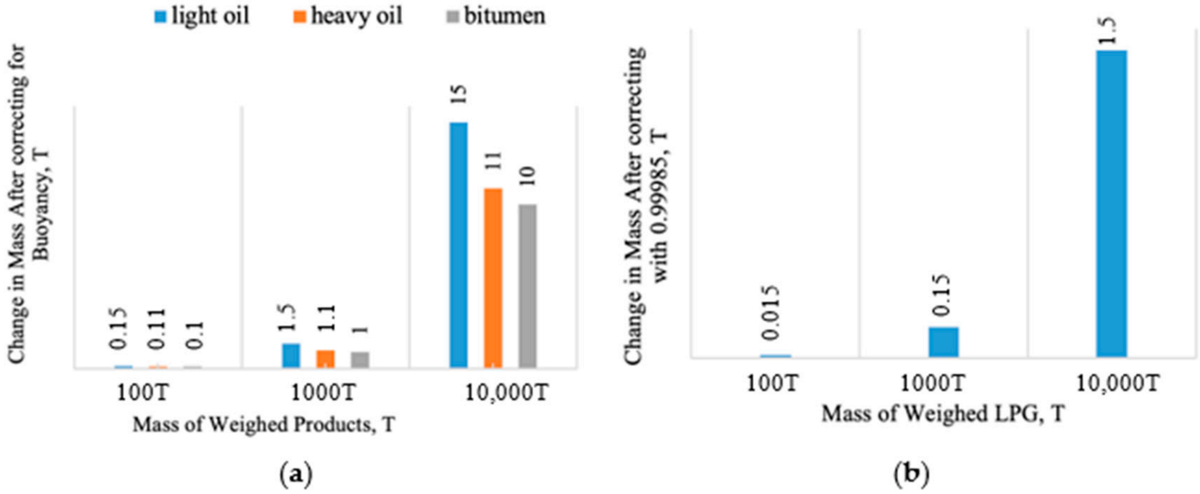


Figure 7. Changes in mass resulting from air buoyancy correction (supplier loss) (**a**) and correction factor of 0.99985 for LPG (client loss) (**b**).

Quantities of these products. The interval from 100 tonnes to 10,000 tonnes is selected for analysis. The results at the top of Figure 7 show that the compensated mass depends on the properties of the product being weighed and the quantity of the product. The lower the density of the product, the greater the losses can be. When weighing small quantities of any product, smaller losses are obtained. When the quantities weighed are from 100 tonnes to 10,000 tonnes, losses can increase from 0.15 tonnes to 150 tonnes. The results presented at the bottom of Figure 7 show how the compensated mass can change with varying quantities of LPG. This means that without inputting the correction factor of 0.99985 for LPG, the client's losses can increase from 0.015 tons to 1.5 tonnes as the weighed quantity of LPG increases from 100 tonnes to 10,000 tonnes.

5.2.3. Specific Mass Changes Due to Buoyancy Corrections

The mass variations due to buoyancy corrections are as follows:

- For light and heavy oils: Changes range from 110 to 150 kg per 100 tonnes (mass corresponds to one-day measurement with one type of measuring instrument), from 1.1 t to 1.5 t per 1000 tonnes, and 11 t to 15 t per 10,000 tonnes.
- For bitumen: Mass changes are about 100 kg per 100 tonnes and 10 t per 10,000 tonnes.

These mass changes have direct implications for pricing and customer satisfaction. Variations in measured mass can lead to pricing inconsistencies, affecting both the profitability for suppliers and the perceived fairness for customers, particularly in high-volume transactions. Addressing these variations through standardized correction protocols could enhance customer confidence and satisfaction while promoting fair pricing practices across markets.

5.2.4. Specific Corrections for LPG Mass Measurements

After applying a correction factor of 0.99985 [47] when weighing LPG, the mass under vacuum is smaller than the measured value. Figure 7 shows the resulting mass changes due to this correction factor. During LPG weighing, if the specified correction factor is not entered, it turns out to be overweight. This overage translates to 15 kg in 100 tonnes, 150 kg in 1000 tonnes, and 1.5 t in 10,000 tonnes.

By correcting the weight of LPG by a factor of 0.99985, a smaller mass is obtained. If the correction factor isn't applied, the customer might pay for excess weight, resulting in a potential financial loss. The significance of these adjustments fluctuates based on the volume of transactions, and companies must evaluate the impact based on monthly, seasonal, or annual purchase-sales volumes. The company itself must consider not only the volume of production but also the price and make the final decision on the significance of the loss.

5.2.5. Impacts on Raw Material Purchases and Sales of Petroleum Products

Corrections that are applied at different stages of the purchase-production-sell process are discussed (Figure 8). When purchasing raw materials or selling products, it is important to follow the general rules for the calculation of the same quantity (Section 2) throughout the purchasing and production chain. Otherwise, any conversions will result in systematic errors, which will accumulate depending on the number of conversions. Specific situations are analyzed by the features of these steps. A negative balance arises when raw materials are purchased based on their mass in a vacuum, while sales are determined by their apparent mass in air. If the mass in air is converted to volume at the same temperature without applying the buoyancy correction, it results in a volume error of 0.14%.

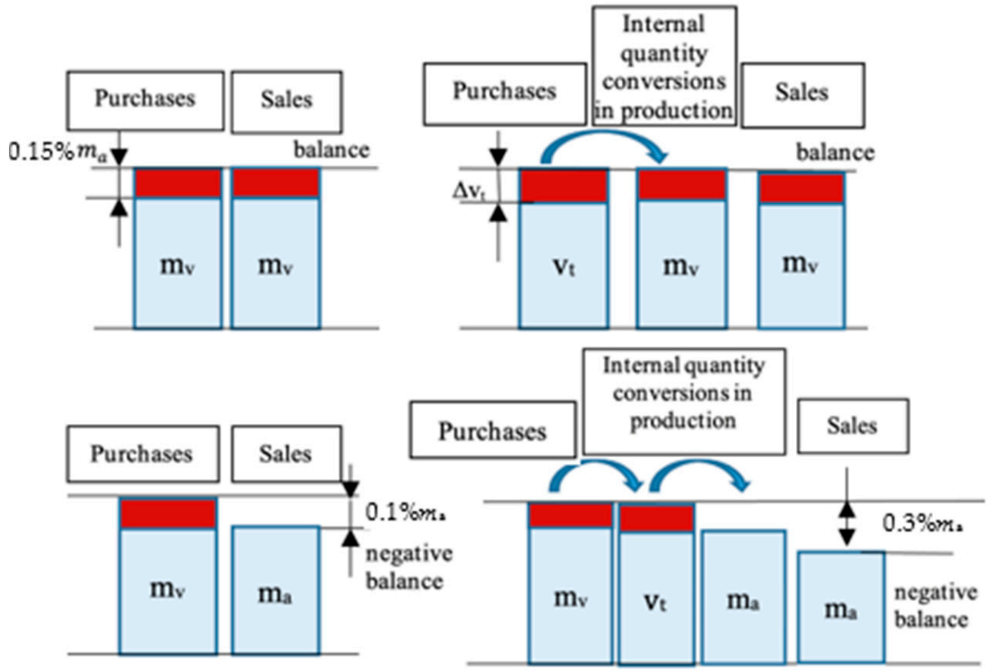


Figure 8. Balance of products obtained by weighing LPP products or using a volumetric method to estimate mass at different stages of the purchase-production-sell.

This error can be eliminated by converting the mass in vacuum at a specific temperature to volume at the same temperature.

5.2.6. Factors Contributing to Measurement Discrepancies

Three main factors contribute to discrepancies when measuring liquid petroleum product quantities. First, measuring instrument errors are simply unavoidable; however, the company chooses the most accurate and practical measurement methods available. Second, systematic errors from unapplied corrections pop up when essential corrections aren't made during the buying or selling of liquid petroleum products. Finally, systematic errors from differing regulations happen because of inconsistent rules about applying or not applying corrections and coefficients for presenting measurement results and for converting mass to volume and vice versa throughout the company's entire purchase, production, and sales process.

5.2.7. Importance of Consistent Reference Conditions in Mass and Volume Calculations

For each goods movement, mass and/or volume should be calculated under reference conditions, considering observed (measured) density and temperature values. This mass and volume calculation method enables clearly defined rules and a basis for price and fee determination, ensuring that "everybody" accepts the stated amount of petroleum product. Volume calculation under reference conditions is achieved using mass in vacuum using the weight correction factor (WCF). Calculation under reference conditions ensures the universally accepted and stated quantity of the petroleum product, aiding in fair and accurate transactions across the entire supply chain.

5.2.8. Practical Potential Implications of Recommendations

Key recommendations include mandating consistent buoyancy correction coefficients and uniform reference conditions for temperature and pressure across the industry. Companies should integrate buoyancy correction protocols, train staff in proper adjustments, and use precise instruments, especially in high-volume transactions. Consistent corrections minimize financial errors, enhance transparency, and prevent losses. Standardized corrections ensure fairness, align with regulations, and promote confidence in trade, benefiting the entire supply chain. A detailed financial analysis of implementing standardized correction protocols could further underscore their importance.

6. Conclusions

This report highlights that comparing quantities measured under diverse environmental conditions (like air temperature, pressure, and density) and with different instruments necessitates establishing normative conditions, especially for temperature. This must align with international and oil industry standards, as well as national regulations. To ensure accurate comparisons, quantitative measurement results (lithe ke volume and weight) require adjustment using specific correction factors. Physically, we can directly compare mass measured by instruments and converted to mass in a vacuum at a reference temperature with mass indirectly calculated from volume and density at the same standard temperature. Any disparities between these masses primarily arise from the precision of the various measuring instruments used for each method. Our proposed consistent result evaluation sequences and result expression methods, based on standardized approaches, ensure the comparability of results obtained through different means and methods. Crucially, all these conclusions hold only when the instruments used meet the characteristics outlined in the standards [9,38,55] and their performance is confirmed through calibration or, if required by legal metrology, through verification procedures.

The simulation of the air buoyancy correction coefficient and its impact on measurement outcomes indicates that buoyancy has a more pronounced effect on the measurement of light petroleum than on heavy petroleum. As a result, the mass in a vacuum rises by

0.15% for light petroleum and by 0.1% for heavy petroleum. These changes are notable, especially in relation to the measurement errors of the instruments used, which range between 0.1% and 0.5%. This implies potential losses between 11 and 15 tonnes per ten thousand tonnes when weighing light and heavy petroleum. Therefore, we acknowledge the significant effect of buoyancy correction on the measurement results of LPP and recommend that any weighing result be corrected by calculating the mass in vacuum. Ultimately, the decision to incorporate buoyancy corrections for weighing petroleum products should be made by the company itself, taking into consideration the actual losses incurred in the broader context of income and costs. The potential financial losses due to neglecting buoyancy correction in a medium-sized refinery can be substantial, reaching approximately $3 million per year in this scenario. Assume that the refinery processes 10,000 tonnes of petroleum products daily, and the average petroleum price for both light and heavy petroleum is $650 per tonne. This highlights the importance of implementing buoyancy correction for accurate mass determination and accounting.

Based on this study, the buoyancy factor is not applicable when weighing LPG in a closed pressure vessel. This is due to the specific properties of the liquid mixture, saturated vapor, and the weighing method used. However, a correction factor of 0.99985 must be applied to the measured result, known as the conventional mass. This correction factor remains constant and does not vary with the type of measuring instrument, the weight of the load, the product composition, or the units of measurement used in the calculation. Consequently, the calculated mass in vacuum in the case of LPG weighing will be lower by approximately 0.015% of the measured value, equivalent to 1.5 tonnes per 10,000 tonnes in favor of the LPG supplier. Its financial impact on a medium-sized refinery is relatively small, approximately $130,000 per year in this scenario. Given that this correction factor is not legally mandated in many countries, and its impact is minor compared to other potential sources of error and loss in the petroleum industry, we recommend against applying it for LPG weighing. This simplifies measurement processes and avoids unnecessary adjustments, especially considering the potential for confusion and disputes that could arise from applying a non-mandatory correction. However, it is crucial for companies to be aware of this potential discrepancy and to have clear contractual agreements with suppliers and customers regarding the measurement and reporting of LPG quantities. Transparency and consistency in measurement practices are essential for maintaining trust and fairness in the petroleum trade.

Although we acknowledge that the buoyancy coefficient does not affect the mass value of LPG in closed tanks, this does not apply to corrections related to the calibration or adjustment of weighing instruments. Therefore, a company's loss management strategy should include investments in higher-precision measuring instruments (e.g., static weighing scales for cars and wagons with a verification scale division value of 20 kg, and 0.2% dynamic weighing scales for wagons). Additionally, regular maintenance of these instruments is crucial. Measurement errors can be reduced by applying known corrections to individual measurement results through calibration and verification protocols. If there are systematic positive or negative deviations in measuring instruments, or if the weighing errors exceed their verification scale interval, a correction may be applied to the measurement results. The results may be uncorrectable if average weighing errors are smaller than the verification scale interval. Ideally, weighing errors should be randomly distributed within the permissible error range for individual measurements. For all operations where applicable, it is advisable to use scales of the same accuracy class, with the same verification scale division value and weighing mode [58,59].

To eliminate inconsistencies arising from the application of air buoyancy corrections and to ensure consistent mass-to-volume conversions in petroleum transactions, it is recommended to establish clear and unequivocal requirements for measurement protocols and the reporting of results. For comparable quantities, only unambiguous results, expressed in consistent units and representing the same physical property, should be compared. When comparing weighing results, direct comparisons (in terms of physical quantities) are valid: $m_{a1} \Leftrightarrow m_{a2}$ (where m_{a1} and m_{a2} represent weighing results in air).

For comparisons between weighing results and volume: $M = m_a \cdot C_{\text{buoyancy}}$, $V_1 = M/\rho_{15}$, $V_2^{15} = V_2^t \cdot VCF_2$, $V_1 \Leftrightarrow V_2^{15}$;

For comparisons between volume and weighing results: $V_1^{15} = V_1^t \cdot VCF_1$, $M_1 = V_1^{15} \cdot \rho_{15}$, $M_2 = m_{a2} \cdot C_{\text{buoyancy}}$, $M_1 \Leftrightarrow M_2$;

For comparisons between two volume measurements: $V_1^{15} = V_1^t \cdot VCF_1$, $V_2^{15} = V_2^t \cdot VCF_2$, $V_1^{15} \Leftrightarrow V_2^{15}$; (where m_a, m_{a2}—mass determined by weighing in air, C_{buoyancy}—air buoyancy correction factor, M, M_1, M_2—mass of product in vacuum (corrected for air buoyancy), ρ_{15}—product density at 15 °C, V_1—volume of product (corrected to reference temperature), V_1^t, V_2^t—volume of product at temperature t, V_1^{15}, V_2^{15}—volume of product corrected to 15 °C, VCF_1, VCF_2—volumetric correction factor (used to convert volume at temperature t to volume at 15 °C)).

To ensure the company's material balance (when purchasing raw materials, in internal production processes, and when selling products) and to minimize losses, it is crucial to adhere to general, uniform quantity calculation provisions throughout the entire purchase-production-sales chain. This means that in all cases, it is necessary to calculate the mass in vacuum and the volume at +15 °C, regardless of whether direct weighing with scales or indirect mass recalculation from volume and density is applied.

This study emphasizes the critical role of precise metrology in the petroleum industry, advocating for standardized measurement protocols and the application of correction factors to minimize accounting losses and enhance trade transparency. It highlights the necessity for stakeholder consensus on measurement methodologies, aligning with international standards and physical principles. To achieve this, investment in high-precision technology and advanced data analytics is recommended. Furthermore, the research underscores the importance of regulatory harmonization to address jurisdictional discrepancies, proposing future investigations into legislative and technological advancements. Ultimately, the implementation of these recommendations will foster a more stable, equitable, and reliable global petroleum market.

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Abbreviations

LPG	Liquefied petroleum gas
ISO	International Organization for Standardization
OIML	International Organization of Legal Metrology
CEN	European Committee for Standardization
WELMEC	European Cooperation in Legal Metrology
EURAMET	European Association of National Metrology Institutes
ASTM	American Society for Testing and Materials
API	American Petroleum Institute
NMIA	National Measurement Institute of Australia
WTO	World Trade Organization
LPP	Liquid petroleum products

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