*International Journal of Latest Research in Engineering and Technology (IJLRET)*
*ISSN: 2454-5031*
*www.ijlret.com || Volume 02 - Issue 10 || October 2016 || PP. 01-09*

# Effects of fuel charges in a three echelon inventory model with variable transportation and carbon emissions

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**Abstract:** The operation of transportation determines the efficiency of moving goods or products. Many firms spent more amounts for the transportation in their total cost of the supply chain. The fuel charges play an important role in thesuccess of transportation for transporting the goods from the origin to destinations. So in this paper we present a three echelon inventory model with Variable Transportation and Variable Carbon emissions along with the fuel charges. Mathematical model and the numerical examples also were presented for the proposedmodel.

**Keywords:** Supply chain, Single setup multi-delivery (SSMD) policy, variable transportation, variable carbon emission, fuel charges

## 1. Introduction:

The role that transportation plays in logistics system is more complex than carrying goods for the proprietors. The main challenges for the system of transportation is that carrying goods and deliver them in a right place or right time in order to satisfy the customer's satisfaction and also the transportation plays a bridge between the producers and consumers, so the transportation cost included with in the ordering cost or setup cost. Nowadays the global supply chain models use the single setup multiple delivery policy instead of using single setup single delivery, but in the single setup multi delivery policy all products are produced in a single setup but it delivers to retailer in multiple deliveries. Therefore the number of transportation is increases for that the variable transportation cost is also added along with the fixed transportation cost in the supply chain model. The advantage of using SSMD is that it can save the holding cost of the retailer. The restriction of using SSMD is that only when the unit holding cost is more than the unit transportation cost of the retailer. In the literature view many authors considers transportation cost in the supply chain model. Cardenas Barron (2007) developed a multi stage supply chain model and he used an algebraic approach to solve his model. He extended the model of khouja (2003) by considering multi stage and derivative-free method to obtain the optimal solution. In the SSMD policy the number of transportation increases which implies the carbon emission is also increases. So the variable and fixed carbon emissions are added in the total cost. The above mentioned two authors did not consider the variable transportation and carbon emission cost.Robers and Cooper (1976) discussed about a fixed charge transportation problem.Burns and Sivazlian(1987) discussed a dynamic analysis of three layer supply chain. Gupta (1992) extended Robersand Cooper's (1976) model with discrete transportation costs, whereas Stenger (1996) extended Burns and Sivazlian's (1987) model by reducing inventories in a multi -echelon manufacturing firm.Wang and Sarker (2005) derived one aspect of the supply chain management with their short term control and SSMD policy. Seo(2006) developed a three stage supply chain by improving reorder decision policy with real –time shared stock information. Park et al. (2010) developed a three stage supply chain network design model with risk pooling and lead times.Roy et al. (2011) proposed an optimal shipment strategy for imperfect items in a stock-out situation. Sana (2011) formulated a three layer supply chain model with a single supplier, manufacturer, and single-retailer with both perfect and imperfect quality of products.Sarkar(2013) developed a two- echelon supply chain model with variable transportation cost with SSMD policy. He did not consider any carbon emission cost. He solved the model with algebraical approach. Recently Cardenas-Barron and Porter (2013) considered a supplychain model for an assembly system with pre-processing of raw materials.Many researchers like Ben-Daya et al. (2013) and Sana et al.(2014) addressed several three layer supply chain model with multiple suppliers,manufacturers,and retailers for multiple items.Cardenas-Barron and Trevino-Garza(2014) made an optimal solution to a three echelon supply chain networkwith multi product and multi period.Cardenas-Barron and Sana(2014) developed a production inventory model for a two echelon supply chain when demand is dependent on sales team'sinitiatives.Yang et al. (2015) discussed about a two stage optimization method for multi objective supply chain network design problem with uncertain transportation costs and uncertain customer demands. Sarkar et al. (2015) extended the concept of Sarkar(2013) with the effect of carbon emission during transporting items from vendor to buyer.

The delivery of finished products from the manufacturer to multi retailer similar type of fixed or some variable transportation costs are involved. Earlier days transportation cost is measured together with the production cost and ordering cost. But nowadays transportation cost of a vehicle involves fixed cost as well as variable cost. The fixed transportation cost is assumed to be a constant sum in each time interval, which indicates some essential expenses of parking fare and rewards to the driver. On the other hand, the variable transportation cost depends mainly on the oil consumed which is related to the distance travelled. Mongia et al. (1991) presented inventory model to reduce the carbon emission cost.Zhao et al (2004) proposed a problem of deciding the optimal ordering quantity and frequency for supplier-retailer logistics system in which transportation cost as well as the multiple uses of the vehicles are considered. Ertogal et al. (2007) considered a vendor buyer inventory model with transportation cost. Wang and Su (2007) discussed an inventory model with a multi echelon production, transportation, and distribution system. Elhedhli and Merrick (2012) derived a green supply chain network design to reduce the carbon emission costs. In this literature view none of the paper considers the fuel cost along with the transportation. So we presenta three echelon inventory model with variable transportation cost and carbon emission cost along with the fuel charges. In this paper we using the single setup multiple delivery policy so this system reduces the whole supply chain cost by reducing the holding cost when the transportation cost and carbon emission cost are not high compared to the holding cost.

The remainder of the paper organised as follows. Problem definition, notations and assumptions for the mathematical model are explained in section 2. Section 3 we provide a Mathematical Model. Numerical examples are explained in section 4. Finally we conclude the paper in section 5.

## 2. Problem definition, notations and assumptions:

In this section we consider the problem definition, notations and assumptions.

**2.1. Problem definition:**

A three echelon supply chain model is considered with a supplier, manufacturer and multi - retailer. Supplier delivers the unfinished products to the manufacturer who transfers them into finished products and transported them into multi retailers. So the players are cooperative to each other for the reduction of the total supply chain cost. Due to the SSMD policy the number of transportation increases and route of transportation may change. Thus the fixed and variable cost is added with the system, due to more transportation the carbon emission cost (both fixed and variable) is added with the total cost. For the success of transportation mainly depends on the fuel charges so we consider the fuel cost in the total supply chain cost. Therefore the main aim of this model is to reduce the supply chain cost by considering SSMD policy, variable transportation, carbon emission and fuel charges.

**2.2. Notations:**

**Decision Variables:**

$T$ **:** common cycle time for multi – retailer (year)

$z_1$ : multiple of the manufacturer's cycle time $T_S = z_1T_m$ ($T_S = z_1z_2T$) (Integer number)

$z_2$ : multiple of the retailer's cycle time $T_m = z_2T$($T_S = z_1z_2T$)(Integer number)

$y_1$ : number of shipment within a cycle for raw materials, accepted by the supplier (Integer number)

$y_2$ : number of shipment within a cycle for unfinished materials, accepted by the manufacturer (Integer number)

**Parameters:**

**Supplier's Parameters**

$P_S$ : production rate of unfinished products (units/year)

$\lambda_S$ : demand rate (units)

$h_{S'}$ : holding cost for raw materials per unit per unit time ($/unit/year)

$h_S$ : holding cost for supplier's finished products and manufacturer's raw materials per unit per unit time ($/unit/year)

$A_S$ : setup cost per setup ($/setup)

$O_S$ : ordering cost per order ($/order)

$Q_S$ : lot size (units)

$G_S$ : shipment size, $G_S = \dfrac{Q_S}{y_1}$ (units)

F : fixed transportation cost ($/shipment)
V : variable transportation cost ($/unit)
$f_1$ : fuel cost for the supplier
d : distance per km
$C_{fcs}$ : fixed carbon emission cost ($/shipment/year)
$C_{vcs}$ : variable carbon emission cost ($/unit/year)
$TC_S$ : total cost per unit time ($/year)

**Manufacturer's Parameters**

$P_m$ : production rate (units/year)
$\lambda_m$ : demand rate (units)
$h_m$ : holding cost for finished products per unit per unit time ($/unit/year)
$A_m$ : setup cost per setup ($/setup)
$O_m$ : ordering cost per order ($/order)
$Q_m$ : lot size of manufacturer (units)
$G_m$ : shipment size received, $G_m = \frac{Q_m}{y_2}$ (units)
F : fixed transportation cost ($/shipment)
V : variable transportation cost ($/unit)
$f_2$ : fuel cost for the manufacturer
d : distance per km
$C_{fcm}$ : fixed carbon emission cost ($/shipment/year)
$C_{vcm}$ : variable carbon emission cost ($/unit/year)
$TC_m$ : total cost per unit time ($/year)

**Retailer's Parameters:**

$\lambda_{rj}$ :demand rate for $j^{th}$ retailer, $\lambda_S = \lambda_m = D = \sum_{j=1}^{n} \lambda_{rj}$ (units)
$h_r$ : holding cost per unit per unit time ($/unit/year)
$O_r$ : ordering cost for retailer ($/order)
n : number of retailers (integer number)
$G_r$ : shipment size for all retailers, $G_S = \frac{Q_S}{y_1}$ (units)
$G_{rj}$ : shipment size for retailer j, $G_r = \sum_{j=1}^{n} G_{rj}$ (units)
$TC_r$ : total cost per unit time ($/year)

To develop the model following assumptions are considered.

**2.3. Assumptions:**

1. A three – echelon supply chain model is considered for single type of products.
2. Inventory holding costs are increasing in the downstream direction due to the value Adding activities carried out on the product as it makes its way down the chain.
3. The manufacturer cycle time is integer multiple of retailer's cycle times and similarly supplier's cycle time is a integer multiple of manufacturer's cycle times.
4. In this model we considers the single – setup – multi- delivery (SSMD) policy, the number of transportation increases so the model assumes a constant and variable transportation cost.
5. In single – setup- multi- delivery, carbon emission is increased due to the number of transportation increased. Therefore we assumed a constant and variable emission cost.
6. Holding cost and ordering cost are assumed same for all retailers in the supply chain.
7. Demand throughout the supply chain is assumed as constant.

## 3. Mathematical Model:

In this model we consider a single supplier, a single manufacturer and multi retailer. The production rate of the semi - finished products by the supplier is $P_S$, these semi- finished products are transported to the manufacturer in equal size of different batches by SSMD policy. The manufacturer makes finished products using the unfinished products of the supplier with a production rate $P_{m.}$ The transportation cost, carbon emission cost andthe fuel cost are assumed for both the suppliers and manufactures. But only the ordering and holding costare used for the retailer's cost.

### 3.1. Cost formulation for the supplier

**Setup cost:**

The supplier distributes the raw materials which fulfils the demand for each cycle, raw material are supplied to the manufacturer to compute production. Therefore, supplier's cycle time is $z_1z_2T$. For every cycle, the supplier gives certain fixed price rates for raw materials supplied. The production setup cost per unit time is,

$$\frac{A_S}{z_1z_2T} \quad (1)$$

**Ordering cost:**

During the cycle time $z_1z_2T$, the supplier's lot size per cycle is $Q_S = z_1z_2TD$, within a set time period, the number of raw material items ($y_1$) bought by the manufacturer from the supplier remains the same for every cycle of transaction.

Therefore, ordering cost for the supplier is = $\frac{O_s y_1}{z_1z_2T}$ (2)

**Holding cost for raw materials:**

The supplier's holding cost per unit per unit time for raw material is,

$$HCS_r = h_s \frac{z_1z_2TD^2}{2y_1P_s} \quad (3)$$

**Holding cost for finished products:**

The supplier's holding cost for the finished product is calculated as,

$$IHC_S = \frac{h_S z_2 T}{2}\left[\left(\frac{2}{y_2} - z_1\right)\frac{D^2}{P_S} + \left(1 - \frac{1}{y_2}\right)\frac{D^2}{P_m} + (z_1 - 1)D\right] \quad (4)$$

**Transportation cost:**

The raw materials are carried by the manufacturer so the supplier bares the transportation cost. Then, the fixed transportation cost is $y_1F$as the number of transportation is $y_1$ and the variable transportation cost as $VQ_S$

The transportation cost is = $\frac{y_1F + VQ_S}{z_1z_2T}$ (5)

**Fuel cost:** the fuel cost for the supplier is = $\frac{f_1 d}{z_1z_2T}$ (6)

**Carbon emission Cost:**

Carbon emission cost depends on product of demand rate of supplier and variable carbon emission costs as $C_{vcs}D$, number of shipment almost with its fixed carbon emission cost $C_{fcs}y_1$.

The Carbon emission cost is = $C_{fcs}y_1 + C_{vcs}D$ (7)

**Total cost per unit time for the supplier is,**

$$TC_S = \frac{A_S + O_S y_1}{z_1z_2T} + h_s \frac{z_1z_2TD^2}{2y_1P_s} + \frac{h_S z_2 T}{2}\left[\left(\frac{2}{y_1} - z_1\right)\frac{D^2}{P_S} + \left(1 - \frac{1}{y_2}\right)\frac{D^2}{P_m} + (z_1 - 1)D\right] + \frac{y_1F + VQ_S}{z_1z_2T}$$
$$+ \frac{f_1 d}{z_1z_2T} + (C_{fcs}y_1 + C_{vcs}D) \quad (8)$$

### 3.2. Manufacturers cost components:

The cost component that concerns the manufacturer are setup cost, ordering cost, raw material holding cost and holding cost of finished products.

**Setup cost:**

The setup cost for the manufacturer is = $\frac{A_m}{z_2 T}$ (9)

**Ordering cost:**

In the SSMD policy the manufacturer produces finished products in a single – setup but transports them by several equal shipments. The manufacturer receives lot size per cycle is $Q_m = z_2TD$,

Thus the ordering cost is = $\frac{O_m y_2}{z_2 T}$ (10)

**Holding cost for raw materials:**

The manufacturer's holding cost per unit per unit time for raw material is,

$$HCS_r = h_s \frac{z_2 T D^2}{2 y_2 P_m} \quad (11)$$

**Holding cost for finished products:**

The holding cost for finished products per unit per unit time is calculated as,

$$IHC_m = \frac{h_m T}{2}\left[(2 - z_2)\frac{D^2}{P_m} + (z_2 - 1)D\right] \quad (12)$$

**Transportation cost:**

The manufacturer transports finished products to the retailer by using some transportation costs. It relates to number of shipments with cost $y_2F$ and variable transportation cost as $VQ_m$

The transportation cost is = $\frac{y_2 F + VQ_m}{z_2 T}$ (13)

**Fuel cost:** the fuel cost for the supplier is = $\frac{f_2 d}{z_2 T}$ (14)

**Carbon emission cost:**

Fixed carbon emission cost of manufacturer is $C_{vcm}D$ and variable cost with respect to the number of receiving shipments with cost $C_{fcm}y_2$ are total carbon emission cost. Thus, the carbon emission cost is = $C_{fcm}y_2 + C_{vcm}D$. (15)

**Total cost per unit time for the manufacturer is,**

$$TC_m = \frac{A_m + O_m y_2}{z_2 T} + h_s \frac{z_2 T D^2}{2 y_2 P_m} + \frac{h_m T}{2}\left[(2 - z_2)\frac{D^2}{P_m} + (z_2 - 1)D\right] + \frac{y_2 F + VQ_m}{z_2 T} + \frac{f_2 d}{z_2 T} + (C_{fcm}y_2 + C_{vcm}D) \quad (16)$$

**3.3. Retailers cost components:**

Ordering cost and inventory holding cost are assumed to be a cost of the retailers.

**Ordering cost:**

The ordering cost for all the retailer is = $\frac{O_r}{T}$ (17)

**Inventory holding cost:**

The holding cost for all the retailer is = $h_r \frac{T\lambda_{rj}}{2}$ (18)

**Total cost per unit time for all retailers is,**

$$TC_r = \sum_{j=1}^{n}\left[\frac{O_r}{T} + h_r \frac{T\lambda_{rj}}{2}\right] \quad (19)$$

**Total cost function = Supplier's cost+ Manufacturer's cost + Retailer's cost**

*$TC(z_1,z_2,T,y_1,y_2)$ =*

$$\frac{T}{2}[z_2\left(\frac{z_1 h_s D^2}{y_1 P_S}-\frac{z_1 h_S D^2}{P_S}+\frac{2h_S D^2}{y_2 P_S}+h_S\left(1-\frac{1}{y_2}\right)\frac{D^2}{P_m}+h_S z_1 D-h_S D-\frac{h_m D^2}{P_m}+h_m D+\frac{h_S D^2}{P_m y_2}\right)$$

$$+\frac{2h_m D^2}{P_m}-h_m D+\sum_{j=1}^{n}\left(h_r\lambda_{rj}\right)]+\frac{1}{T}\left(\frac{1}{z_2}\left(\frac{A_S+O_S y_1}{z_1}+A_m+O_m y_2\right)+\sum_{j=1}^{n}O_r\right)+\frac{y_1 F+f_1 d}{z_1 z_2 T}$$

$$+ 2VD + \frac{y_2 F+f_2 d}{z_2 T} + C_{fcs}y_1 + C_{vcs}D + C_{fcm}y_2 + C_{vcm}D \quad (20)$$

$$TC(z_1,z_2,T,y_1,y_2) = TY + \frac{W_1+W_2}{T} + (\alpha_3+\alpha_4+\alpha_5) \quad (21)$$

{See Appendix A for all values}

Differentiating the equ (21) w.r.to 'T' we get the optimal value of common cycle time of multi retailer T,

$$T^* = \sqrt{\frac{(W_1+W_2)}{Y}} \quad (22)$$

Substituting $T^*$ in the cost equation so the total cost function is expressed as,

$$TC(z_1,z_2,y_1,y_2) = 2\sqrt{Y(W_1+W_2)}+\alpha_3+\alpha_4+\alpha_5 \quad (23)$$

Now the optimal $T^*$ is dependent on $z_1,z_2,y_1$,and,$y_2$. The algebraical method is applicable for the optimum values of $z_1,z_2,y_1$,and $y_2$. The model takes only that part which consists of the decision variables. Substituting the values of Y and W we can obtain,

$$TC(z_1,z_2,y_1,y_2) = 2\sqrt{\left(\frac{z_2\psi_2+\alpha_2}{2}\right)\left(\frac{\phi_2}{z_2}+\sum_{j=1}^{n}O_r+\frac{(y_1F+f_1d)}{z_1z_2}+\frac{(y_2F+f_2d)}{z_2}\right)} \quad (24)$$

It can be further simplified as,

$$= \sqrt{2}\sqrt{\left(\sqrt{z_2\psi_2R_2}-\sqrt{\frac{\alpha_2R_1}{z_2}}\right)^2+2\sqrt{\psi_2R_2}\sqrt{\alpha_2R_1}+\psi_2R_1+\alpha_2R_2} \quad (25)$$

{See Appendix B for all values}

Solving the equation for fixed values of $z_1$, $y_1$, $z_2$ and $y_2$ we will get the optimum value for the integer multiplier $z_2$ can be expressed as,

$$z_2^* = \sqrt{\frac{\alpha_2R_1}{\psi_2R_2}} \quad (26)$$

Thus the cost function with respect to other three decision variables $z_1,y_1$ and $y_2$ is

$$TC(z_1,y_1,y_2) = \sqrt{2}\left(\sqrt{\psi_2R_1}+\sqrt{\alpha_2R_2}\right)+\alpha_3+\alpha_4+\alpha_5 \quad (27)$$

To compute the optimum value of $z_1$, we consider the model that takes only the part of $z_1$ as follows,

$$\sqrt{\psi_2R_1} = \sqrt{z_1\psi_1R_3+\frac{\alpha_1\left[\left(y_1F+f_1d\right)+\phi_1\right]}{z_1}+R_4} \quad (28)$$

{See Appendix C for all values}

Solving the above equation with respect to $z_1$ we get the optimal value of multiple integer $z_1$ as follows,

$$z_1^* = \sqrt{\frac{\alpha_1\left[\left(y_1F+f_1d\right)+\phi_1\right]}{\psi_1R_3}}$$

Therefore the total cost function is,

$$TC(y_1,y_2) = \sqrt{R_4+2\sqrt{\alpha_1\left[\left(y_1F+f_1d\right)+\phi_1\right]\psi_1R_3}}+\alpha_3+\alpha_4+\alpha_5 \quad (29)$$

Simplified the above equation and we get the following expressions, TC ($y_1$,$y_2$) $= \sqrt{\left(\sqrt{\alpha_1 R_3} + \sqrt{\psi_1\left[\left(y_1 F + f_1 d\right) + \phi_1\right]}\right)^2 + \left(\sqrt{C_{fcs} y_1}\right)^2}$

Taking the parts of which are functions of $y_1$ and solving it we can obtain the optimal order quantity of $y_1$,

$$y_1^* = \sqrt{\frac{h_{S'} D^2 \left(A_S + f_1 d\right)}{P_S\left(C_{fcs} + O_s R_5 + FR_5\right)}} \qquad (30)$$

{See Appendix D for all values}

Now the remaining cost function $y_2$ can be calculated as in a following manner,

$$\text{TC}(y_2) = \sqrt{\alpha_1 R_3} + \alpha_4 + \alpha_5 + 2\sqrt{\frac{h_{s'} D^2\left(A_S + f_1 d\right)}{P_S}\left(C_{fcs} + FR_5 + O_S R_5\right)} + R_6 \qquad (31)$$

Solving the above equation with respect to $y_2$, we get the optimal value of integer multiplier $y_2$ as follows,

$$y_2^* = \sqrt{\frac{2h_S D^2\left(A_m + f_2 d\right)}{P_S\left(C_{fcm} + O_m R_7 + FR_7\right)}} \qquad (32)$$

And the corresponding total cost function as,

$$TC = \alpha_5 + 2\sqrt{\frac{h_{s'} D^2 (A_S + f_1 d)}{P_S}\left(C_{fcs} + FR_5 + O_S R_5\right)} + 2\sqrt{2\frac{h_S D^2 (A_m + f_2 d)}{P_s}\left(C_{fcm} + FR_7 + O_m R_7\right)}$$

$$+ R_6 + R_8 \qquad (33)$$

{See Appendix E for all values}

The model is optimized analytically, now the model tested with the numerical example in the next section.

## 4. Numerical Examples:

In this section we provide the numerical example for the proposed model. The following data is used for finding the result. $O_S$ = \$300/order, $O_m$ = \$150/order, $h_{S'}$ = \$0.6 \$/unit/year, $h_S$ = \$0.4 \$/unit/year, $h_m$ = \$5/unit/year, $A_S$ = \$ 500/setup, $A_m$= \$200/setup , $P_S$ = 2990 units/year, $P_m$ = 1900 units/year, $h_r$ =\$5/unit/year, $O_r$ = \$30/order, $\lambda_{rj}$ =100 units, $C_{fcm}$ =\$0.2/shipment/year,$C_{fcs}$ =\$0.2/shipment/year, $C_{vcm}$ = \$0.1/unit/year, $C_{vcs}$ = \$0.1/unit/year,F=\$0.2/shipment,V=\$0.1/unit, d=10km, $f_1$=$f_2$= \$54/litre.

The retailer's annual total cost function for cycle time $T$ = 0.9,integer multiplier of the manufacturer's cycle time$z_1$=3.18, integer multiplier of the retailer's cycle time $z_2$=2, number of raw material shipments received by supplier within a cycle $y_1$ = 0.28, number of raw material shipments received by manufacturer within a cycle $y_2$ = 0.2, finally the total cost of the system is (i.e.)TC = 1296

## 5. Conclusion:

In this we consider a three echelon inventory model with variable cost and variable carbon emission, and also we derived the model under the effect of fuel charges. Fuel is the energy for vehicles for moving the products. The main aim of this paper is to reduce the total cost of the system. From the numerical result we can able to find that the after considering the fuel charges it would reduce the total cost of the system.

**Appendix A:**

$$\psi_1 = \frac{h_{S'} D^2}{y_1 P_S} + h_S D(1 - \frac{D}{P_S}),\ \psi_2 = z_1\psi_1 + \alpha_1,\ Y = \frac{z_2\psi_2 + \alpha_2}{2}$$

$$\alpha_1 = \frac{2h_S D^2}{y_2 P_S} + h_S\frac{D^2}{P_m} - h_S D - \frac{h_m D^2}{P_m} + h_m D, \alpha_2 = \frac{2h_m D^2}{P_m} - h_m D + \sum_{j=1}^{n} h_r\lambda_{rj}, \phi_1 = A_S + O_S y_1,$$

$$\phi_2 = \frac{\phi_1}{z_1} + A_m + O_m y_2, W_1 = \frac{\phi_2}{z_2} + \sum_{j=1}^{n} O_r, W_2 = \frac{(y_1 F + f_1 d)}{z_1 z_2} + \frac{(y_2 F + f_2 d)}{z_2}, \alpha_3 = C_{fcs} y_1 + C_{vcs} D,$$

$$\alpha_4 = C_{fcm} y_2 + C_{vcm} D,$$

$\alpha_5 = 2VD$

**Appendix B:**

$$R_1 = \phi_2 + \frac{y_1 F}{z_1} + \frac{f_1 d}{z_1} + y_2 F + f_2 d$$

$$R_2 = \sum_{j=1}^{n} O_r$$

**Appendix C:**

$$R_3 = A_m + O_m y_2 + y_2 F + f_2 d$$

$$R_4 = \left(A_m + O_m y_2\right)\alpha_1 + y_2 F \alpha_1 + f_2 d \alpha_1 + \psi_1 y_1 F + \psi_1 f_1 d + \psi_1 \phi_1$$

**Appendix D:**

$$R_5 = h_S D(1 - \frac{D}{P_S})$$

$$R_6 = \frac{h_{S'} D^2 O_S}{P_S} + R_5 A_5 + C_{vcs} D + \frac{h_{S'} D^2 F}{P_S} + f_1 d R_5$$

**Appendix E:**

$$R_7 = \frac{h_S D^2}{P_m} - h_S D - \frac{h_m D^2}{P_m} + h_m D$$

$$R_8 = \frac{2 h_S D^2 O_m}{P_S} + R_7 A_m + C_{vcm} D + \frac{2 h_{S'} D^2 F}{P_S} + f_2 d R_7$$

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