USING QUEUEING THEORY TO FIND THE OPTIMAL CHARACTER-VEHICLE COMBINATION FOR 150CC MARIO KART WORLD RACES

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SUMMARY

This investigation entailed using Queueing Theory to determine the probabilities of possessing any given number of coins during a race, evaluating the expected overall speed of each possible character-vehicle combination according to its speed increase from its speed attribute for each terrain and weight-dependent coin effects, and finding the combination with the highest expected overall speed while fulfilling a minimum requirement for acceleration to find the optimal character-vehicle combination for 150cc races in Mario Kart World.

The optimal character-vehicle combination was found to be a flyweight character (i.e. Swoop, Para-Biddybud, Baby Peach, or Baby Daisy) with the Reel Racer, with viable alternatives being a solid-focused featherweight character (i.e. Spike, Goomba, or Baby Mario) with the W-Twin Chopper, a solid-focused middleweight character (i.e. Mario or Rocky Wrench) with the Baby Blooper, and a solid-focused cruiser character (i.e. Pauline, Snowman, or Piranha Plant) with the Mach Rocket or R.O.B. H.O.G..

The results of this investigation demonstrate that speed on solid terrain should be emphasised over speed on grainy and water terrains. The low weight attribute of two of the four best combinations also highlights the importance of minimising weight when selecting a character and vehicle for racing in Mario Kart World.

All spreadsheets and Python scripts involved in this investigation are available in the folder in which this report resides.

ACKNOWLEDGEMENTS

Special acknowledgements to my Manufacturing Engineering lecturer in my final year at university for teaching me Queueing Theory, and my best friend and former coursemate for inspiring me to become proficient in Python.

Acknowledgements also to the members of the Mario Kart World community who came before me and made available the data necessary to perform this investigation.

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LIST OF SYMBOLS

$\varepsilon = relative\ speed\ increase$
$s = speed\ attribute$
$c = number\ of\ coins\ in\ possession$
$w = weight\ attribute$
$t = terrain\ identifier$
$\lambda = coin\ collection\ rate\ (\mathrm{min}^{-1})$
$\mu = coin\ dispossession\ rate\ (\mathrm{min}^{-1})$
$r = coin\ reset\ rate\ (i.e. frequency\ of\ races)\ (\mathrm{min}^{-1})$
$P = coin\ possession\ probabilities$
$d_1, d_2, d_3, a_1, a_2 = intermediate\ calculation\ variables$
$E = Expected\ overall\ speed\ increase\ relative\ to\ the\ baseline$

1. INTRODUCTION

Selecting an optimal character-vehicle combination is essential for maximising one's chances of winning races in Mario Kart World. Members of the Mario Kart World community have found the performance attributes (i.e. speed, acceleration, weight, and handling) of each character and vehicle and how they interact with the in-game mechanics (e.g. *MK World Builder* [1], *Mario Kart World Stats* [2], and *The Mario Kart World Stratpedia* [3]), including how each coin's effect on the racer's speed depends on the number of coins in possession and the racer's weight attribute, but the probability distribution of the number of coins in possession from 0 to 20 for a racer at any given moment and, by extension, the expected overall speed for each character-vehicle combination, has yet to be derived until this investigation.

Therefore, this investigation aimed to find the optimal character-vehicle combination in 150cc Mario Kart World races by maximising the expected overall speed while maintaining a reasonable acceleration. This investigation was conducted via the following objectives:

a. Apply Queueing Theory to determine the probabilities of possessing any given number of coins during a race from 0 to 20.
b. Evaluate the expected overall speed of each possible character-vehicle combination, according to its speed increase from its speed attribute for each terrain and weight-dependent coin effects, using the coin possession probabilities.
c. Find the minimum requirement for the acceleration attribute for a viable character-vehicle combination.
d. Find the character-vehicle combination with the highest expected overall speed that meets or exceeds the acceleration requirement.

2. RELEVANT GAME MECHANICS

The background information relevant to this investigation is as follows.

2.1. Speed attribute, coins, and weight attribute

For each terrain, the speed attribute increases the racer's 0-coin speed linearly from a baseline, and coins increase the racer's speed by up to 5% of the racer's 0-coin speed at 20 coins, where the weight attribute determines the rate at which each coin, from the 1st to the 20th, increases the racer's speed (Figure 1) [3].

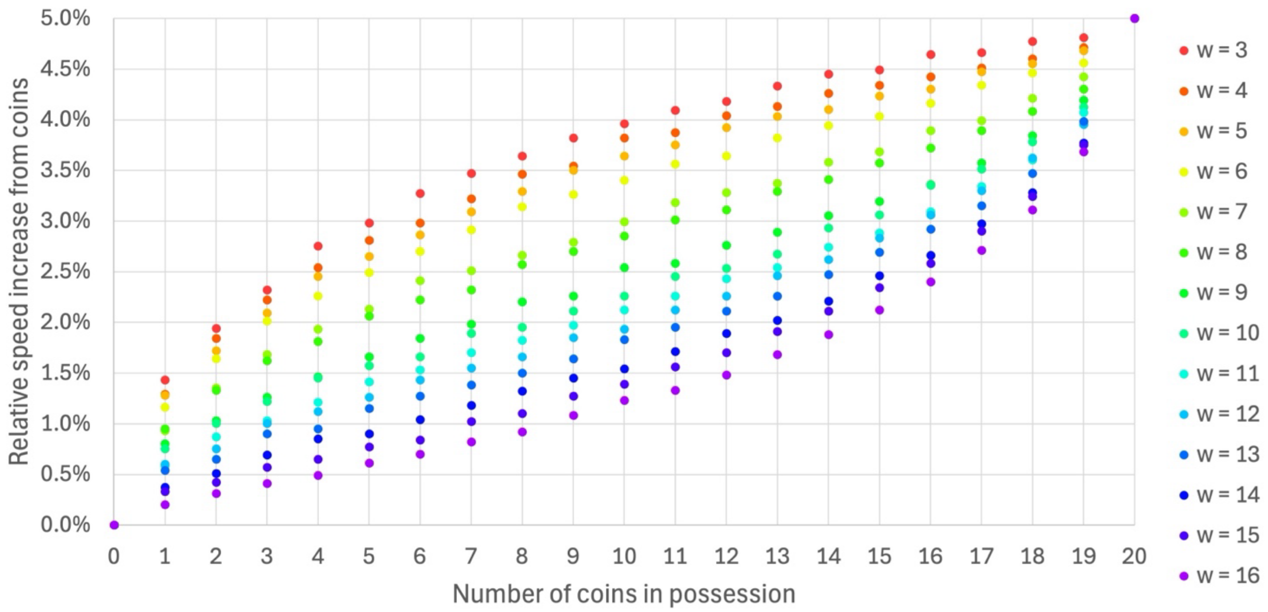

Figure 1. A simultaneous plot of $\boldsymbol{\varepsilon_{c,w}}$ *vs the number of coins in possession for* $\boldsymbol{w} = 0,1,2,\dots,13$.

$\varepsilon = relative\ speed\ increase$

$s = speed\ attribute$
$c = number\ of\ coins\ in\ possession$
$w = weight\ attribute$
$t = terrain\ identifier$
(lowercase means specific and uppercase means averaged)

$$\varepsilon_{s,t} \approx 1 + 0.312\% \cdot s_t \tag{1}$$

$$\varepsilon_{s,t,c,w} = (1 + \varepsilon_{s,t})(1 + \varepsilon_{c,w}) - 1 \tag{2}$$

There are three terrains in Mario Kart World. They are solid (e.g. asphalt, brick, metal, carpet, wood, ice), grainy (e.g. sand, soil, snow), and water. The solid, grainy, and water terrains constitute 63.25%, 26.69%, and 10.07% of all roads in Mario Kart World [3]. These proportions inform the weighted mean speed increase. (A correction factor was imposed to account for the rounding error.)

$$\varepsilon_{s,T,c,w} = \frac{0.6325 \cdot \varepsilon_{s,solid,c,w} + 0.2669 \cdot \varepsilon_{s,grainy,c,w} + 0.1007 \cdot \varepsilon_{s,water,c,w}}{1.0001} \tag{3}$$

2.2. Acceleration requirement

Meanwhile, the acceleration attribute determines the duration required to get to top speed from zero and the duration of boosts from drifting and tricking. Inspecting the data on the boost duration and the zero-to-top-speed duration finds that the benefits from increasing the acceleration attribute past 12 points become limited (Figure 2 and Figure 3) [3].

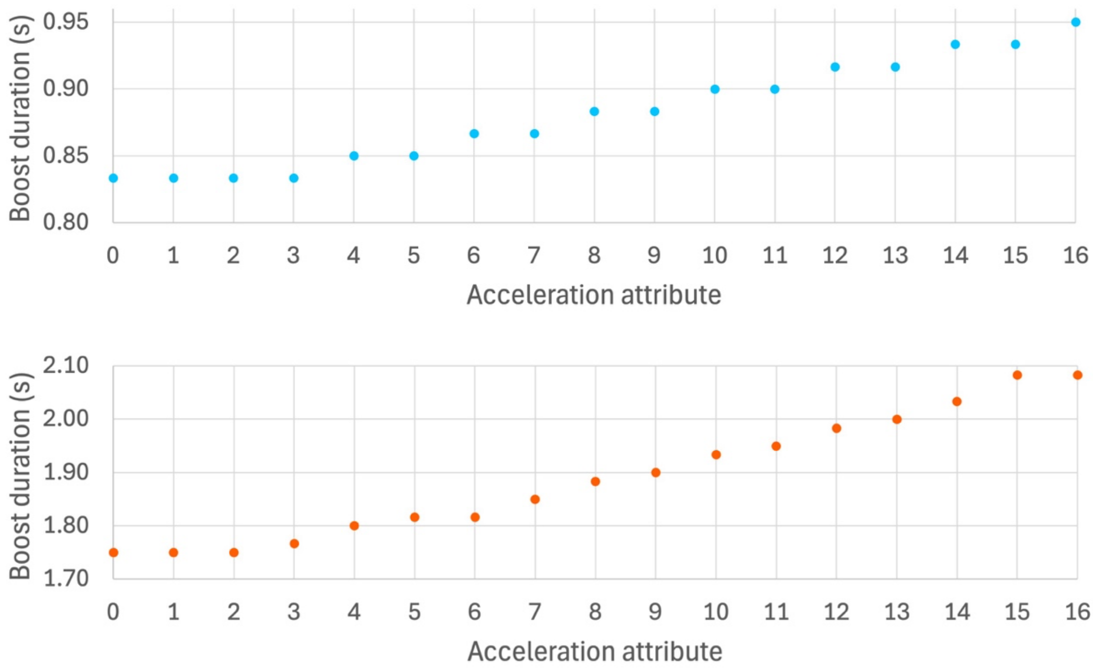

Figure 2. The boost durations for a mini-turbo (blue; top) and a super mini-turbo (orange; bottom) as the acceleration attribute increases from 0 to 16 points.

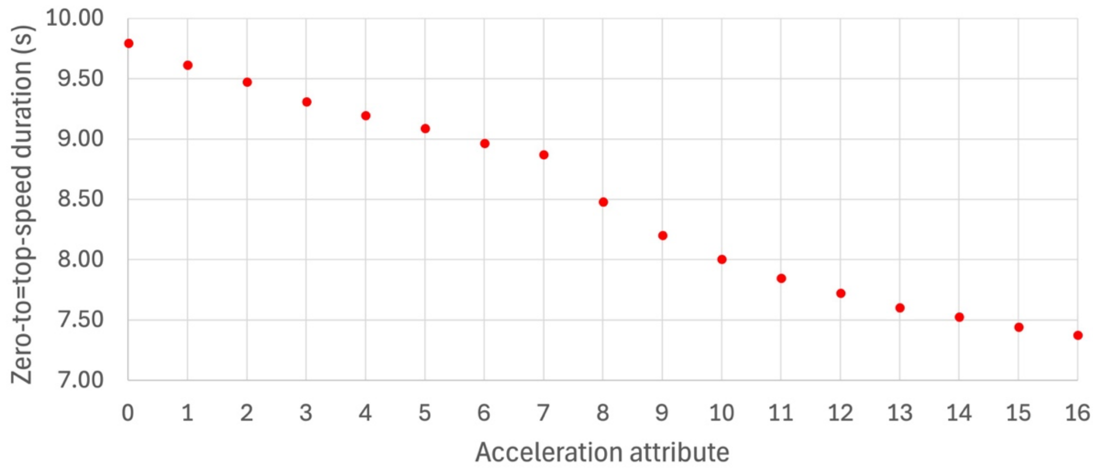

Figure 3. The zero-to-top-speed duration as the acceleration attribute increases from 0 to 16 points.

The acceleration attribute for each character-vehicle combination is constant across all terrains.

3. METHOD

The method used in this investigation is as follows.

3.1. The Markov chain of coin possession

In Queueing Theory, each possible number of coins in possession, from 0 to 20, is treated as a state. In this model, collecting coins means moving to a higher state and dispossessing coins, either by being hit by an item, running into an obstacle, falling off track and requiring Lakitu to intervene, or finishing a race and starting a new one, means moving to a lower state. Given that coins are collected one at a time, each mid-race dispossession is 3 coins or the entire possession, whichever is less, and coin possessions reset at the start of each race to between 0 and 5 coins depending on the racer's position, the model of the coin possession probabilities can be illustrated as follows.

$\lambda = coin\ collection\ rate\ (\mathrm{min}^{-1})$
$\mu = coin\ dispossession\ rate\ (\mathrm{min}^{-1})$
$r = coin\ reset\ rate\ (i.e. frequency\ of\ races)\ (\mathrm{min}^{-1})$
$P = coin\ possession\ probabilities$

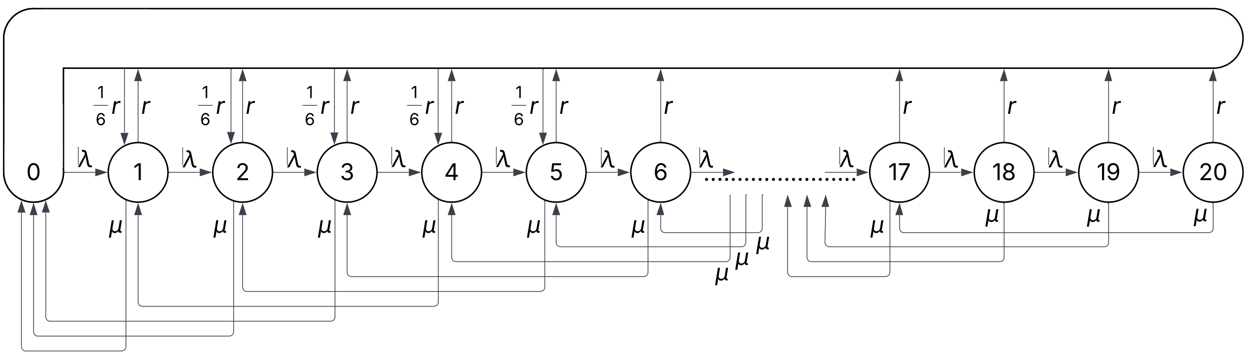

Figure 4. The Markov chain for coin possession in a 150cc Mario Kart World race.

Since the inflows and outflows at each state are balanced for any system at equilibrium, the following equations were derived.

$$-\lambda P_0 + \left(\mu + \frac{5}{6}r\right)(P_1 + P_2 + P_3) + \frac{5}{6}r(P_4 + P_5) + r(P_6 + P_7 + \cdots + P_{20}) = 0 \qquad (4)$$

$$for\ 1 \le c \le 5, \qquad \lambda P_{c-1} - \left(\lambda + \mu + \frac{5}{6}r\right)P_c + \mu P_{c+3} = 0 \qquad (5)$$

$$for\ 6 \le c \le 17, \qquad \lambda P_{c-1} - (\lambda + \mu + r)P_c + \mu P_{c+3} = 0 \qquad (6)$$

$$for\ 18 \le c \le 19, \qquad \lambda P_{c-1} - (\lambda + \mu + r)P_c = 0 \qquad (7)$$

$$\lambda P_{19} - (\mu + r)P_{20} = 0 \qquad (8)$$

$$and\ by\ definition, \qquad P_0 + P_1 + P_2 + \cdots + P_{20} = 1 \qquad (9)$$

Substituting Equation 8 into Equation 7 when $\boldsymbol{c} = 19$ yields the following matrix-vector equation.

$$-\left(\lambda+\mu+\frac{5}{6}r\right)\to d_1,\qquad -(\lambda+\mu+r)\to d_2,\qquad -(\mu+r)\to d_3,\qquad \left(\mu+\frac{5}{6}r\right)\to a_1,\qquad \frac{5}{6}r\to a_2$$

$$\begin{bmatrix}
-\lambda & a_1 & a_1 & a_1 & a_2 & a_2 & r & r & r & r & r & r & r & r & r & r & r & r & r & r & r \\
\lambda & d_1 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \lambda & d_1 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \lambda & d_1 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_3 & d_3 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}\cdot\begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \\ P_8 \\ P_9 \\ P_{10} \\ P_{11} \\ P_{12} \\ P_{13} \\ P_{14} \\ P_{15} \\ P_{16} \\ P_{17} \\ P_{18} \\ P_{19} \\ P_{20} \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{10}$$

3.2. Finding the coin collection, dispossession, and reset rates

An hour-long YouTube video of Mario Kart World online gameplay uploaded by Shortcat [4] was watched. The numbers of occurrences of coin collections and dispossessions were counted and the race times were recorded. The coin collection and dispossession occurrences were divided by the total racing time to find $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$, and $\boldsymbol{r}$ was evaluated by the number of races divided by the total racing time.

3.3. Evaluating the expected overall speed

For each of the 480 unique character vehicle combinations (from 20 unique character classes and 24 unique vehicle attribute profiles), after evaluating $\boldsymbol{\varepsilon_{s,T,c,w}}$ for all $1 \le \boldsymbol{c} \le 20$ using Equations 1 to 3, the expected overall speed increase relative to the baseline during 150cc races $\boldsymbol{E}$ was evaluated by the dot product of the $\boldsymbol{\varepsilon_{s,T,c,w}}$ magnitudes and the coin possession probabilities.

$$E = Expected\ overall\ speed\ increase\ relative\ to\ the\ baseline$$

$$E = \varepsilon_{s,T,C,w} = \sum_{c=0}^{20} P_c \cdot \varepsilon_{s,T,c,w} \tag{11}$$

Then, finding the optimal character-vehicle combination comprised eliminating all combinations with acceleration attributes less than 12 points and identifying the combination with the highest $\boldsymbol{E}$ among all the remaining combinations.

4. RESULTS

First, the following coin collection, dispossession, and reset rates were found (Table 1).

Table 1. The data collected on coin collection, dispossession, and resets [4].

Total number of			**Total racing time** (min)	λ (min^{-1})	μ (min^{-1})	r (min^{-1})
Coins collected	**Dispossessions**	**Races**				
411	61	20	46.40	8.858	1.315	0.4310

The coin possession probabilities were found to be higher towards 0 coins and at 19 coins or 20 coins (Figure 5). This trend is supported by anecdotal evidence from gameplay, as frontrunning and sandbagging both enable the racer to collect coins easily, chaos in the racer pack in median positions tends to minimise coin possession, and there are no known phenomena to keep coin possession counts away from the extremes.

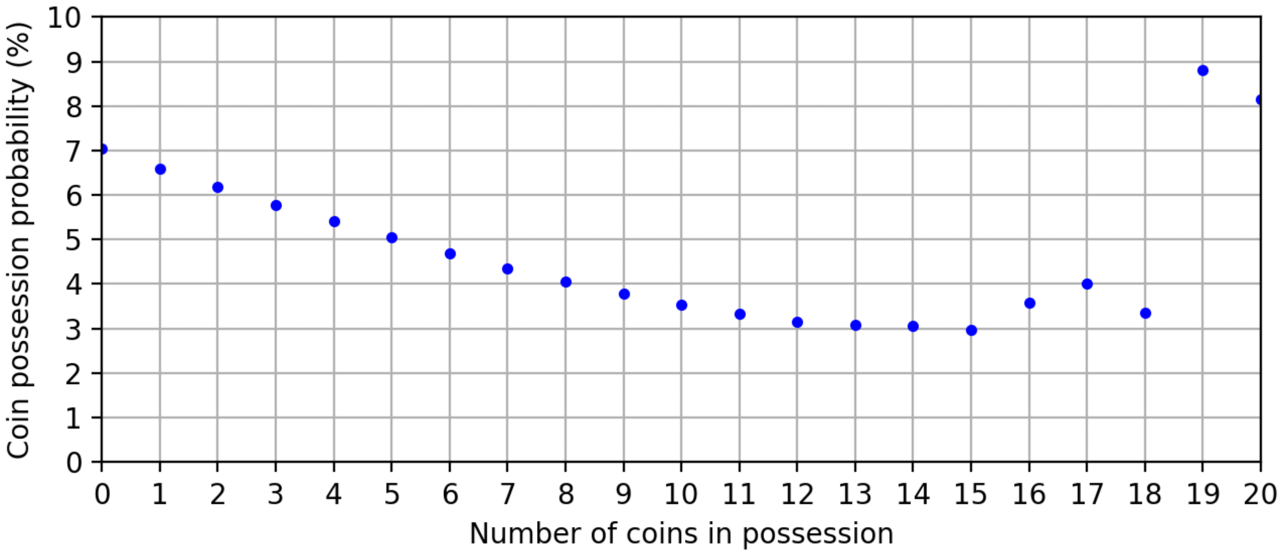

Figure 5. A graph of P_c versus c.

In light of the coin possession probabilities, the optimal character-vehicle combination was found to be a flyweight character (i.e. Swoop, Para-Biddybud, Baby Peach, or Baby Daisy) with the Reel Racer at $E_{max} \approx 6.576\%$, with viable alternatives at $0.98E_{max}$ or above being a solid-focused featherweight character (i.e. Spike, Goomba, or Baby Mario) with the W-Twin Chopper, a solid-focused middleweight character (i.e. Mario or Rocky Wrench) with the Baby Blooper, and a solid-focused cruiser character (i.e. Pauline, Snowman, or Piranha Plant) with the Mach Rocket or R.O.B. H.O.G.. Table 2 lists all the attributes and E magnitudes for the aforementioned combinations. Figure 5 shows their $\varepsilon_{s,T,c,w}$ versus c profiles.

Table 2. The attribute profile of the optimal combination and the viable alternatives.

Character Vehicle	Attributes								E (%)
	Speed			Acceleration	Weight	Handling			
	Solid	Grainy	Water			Solid	Grainy	Water	
Flyweight Reel racer	11	11	11	12	6	13	13	13	6.576
Solid featherweight W-Twin Chopper	11	10	10	12	6	15	13	13	6.458
Solid middleweight Baby Blooper	14	8	8	12	8	16	10	10	6.454
Solid cruiser Mach Rocket	14	8	8	12	8	16	10	10	6.454

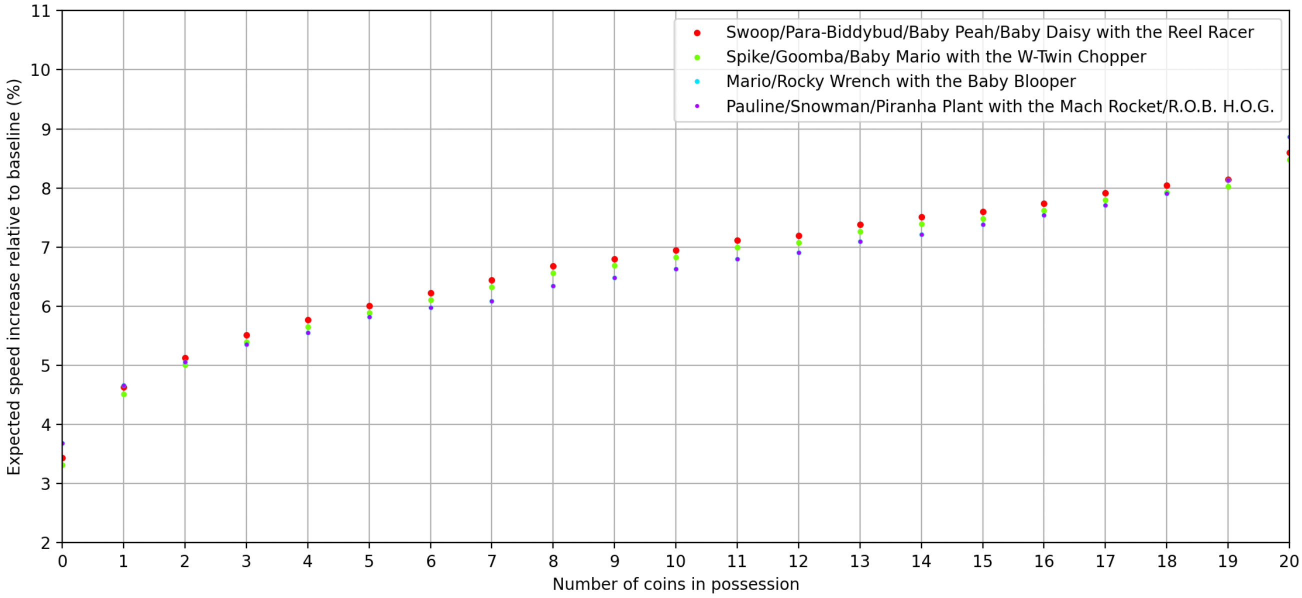

Table 3. A simultaneous plot of the $\varepsilon_{s,T,c,w}$ versus c profiles of the optimal combination and the viable alternatives.

The Reel Racer was featured in the optimal character-vehicle combination because it offered the most speed for minimum weight at 8 points for the speed attribute on every terrain versus 3 points for the weight attribute. The solid-focused featherweight character with the W-Twin Chopper, being second best, differed from the optimum by exchanging 1 point each of the speed attribute on the less emphasised grainy and water terrains for 2 extra points for solid handling. The solid-focused middleweight character with the Baby Blooper and the solid-focused cruiser character with the Mach Rocket, being functionally identical and third best, placed emphasis on solid terrain at the expense of speed in grainy and water terrains. Combinations that sacrificed speed in grainy and water terrains in favour of speed in solid terrain remained successful, as solid terrain formed most of the roads in Mario Kart World.

Minimising weight has unsurprisingly proven crucial in optimising racing performance, as increasing weight dampens the ability of coins to increase the racer's speed.

5. CONCLUSION

To conclude, by using Queueing Theory to determine the probabilities of possessing any given number of coins during a race, evaluating the expected overall speed of each possible character-vehicle combination according to its speed increase from its speed attribute for each terrain and weight-dependent coin effects, and finding the combination with the highest expected overall speed while fulfilling a minimum requirement for acceleration, this investigation has found the optimal character-vehicle combination for 150cc races in Mario Kart World.

The results of this investigation demonstrate that speed on solid terrain should be emphasised over speed on grainy and water terrains. The low weight attribute of two of the four best combinations also highlights the importance of minimising weight when selecting a character and vehicle for racing in Mario Kart World.

The aim of this investigation was achieved successfully.

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