Anthropogenic heat implications of Colombo core area development plan

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Abstract. Statistics on energy use and built density portrays Colombo as the largest consumer of energy and most significant producer of waste heat in Sri Lanka, and the city is facing extensive growth permitted by current development plans. However, Colombo Core Area is threatened by Urban Heat Island effect (UHI). Anthropogenic heat impact on UHI is crucial and its future trends need to be studied before facilitating further development. In this paper we use Local Climate Zone classification to typify the study area into zones of similar climate. This is then integrated with population data, building electricity consumption and vehicle counts to map anthropogenic heat emission at local scale, under current and projected land-use change in Colombo. Results reveal that building waste heat makes the highest impact, in comparison to vehicle and metabolic heat. Thus, building density change, electricity consumption in each building and projected land use change, could have greater impact on anthropogenic heat flux at neighbourhood scale, which would further exacerbate the UHI problem at city scale.

1. Introduction
Cities are cores of urbanization and are often drivers of economy in a country. Hence development proposals are constantly upgraded to meet the growing political and socio-economic demands. This may lead to overlooking their long-term environmental impacts against the immediate benefits. Excessive non-renewable energy consumption in cities results in the release of additional waste heat to the atmosphere. This is a significant contributor to the Urban Heat Island (UHI) phenomenon and is known as the Anthropogenic Heat Flux (AHF), which represents climatic impacts caused by human activity.
Multiple research state developing warm humid tropics will be most affected from negative environmental impacts of the UHI effect. Colombo, Sri Lanka easily fits this category and is now earmarked for extensive future development under the Colombo Core Area Development Plan (CCADP). The city is already threatened by the UHI effect due to concentrated, haphazard development, land use change and expected increase in building density within the city [1].
Acknowledging sources of anthropogenic heat emission is an essential initiative step to mitigate UHI effect, before facilitating further development in Colombo. This defines the parameters explored in this research as following:
How do the proposed developments affect land use and building density in the Colombo Core Area (CCA) and thus, the impact of Anthropogenic Heat Flux on the UHI effect? What changes in AHF intensity can be expected with the 2030 proposed developments?
What is the magnitude of impact of the three sources of anthropogenic heat? – Waste heat emission from buildings (based on building scale, typology of use and energy consumption at building scale), the impact of vehicle heat emission (relationship between vehicle counts, types and waste heat emission per vehicle) and the impact of metabolic heat (indications on demographic data) to the overall anthropogenic heat emission in the region. The scope of the study is limited to the ‘Colombo Core Area Development Plan’ (CCADP), under the larger umbrella of Western region Megapolis Planning Project of the Ministry of Megapolis and Western Development, Sri Lanka (See www.megapolismin.gov.lk) [2]. The in-depth mapping is focused on Colombo 02 administrative zone, as a representative case study. To overcome challenges in an inventory method, a locally feasible method that adopts the Local Climate Zones (LCZ) classification along with a customized urban energy balance model is used to evaluate the built environment at a macro-scale, which can be further developed in future to study impacts at micro-scale. Accordingly, this research lays a foundation for further, detailed research on AHF to determine methods to mitigate its impacts. It creates awareness on possible environmental impacts from urban areas earmarked for development in Colombo, while urging the need to design climate conscious cities in general.

2. Background

2.1. Anthropogenic Heat Flux as a cause for Urban Heat Island
Urban Heat island effect is caused by accumulation of heat, especially in densely built areas due to alterations in natural surface energy and radiation balances. Research reveals that atmospheric heat gain leading to UHI is correlated with population density and morphology of the city such as its size, and arrangement of neighbourhoods. This suggests a strong impact from demographic aspects and waste heat emission from various artificial sources. Thus, AHF is a significant component in the energy balance model [3] as it represents the artificial addition of heat to the surface energy balance. Some significant determinants of anthropogenic heat are population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy. Thus, anthropogenic heat flux is measured as a flow of energy per unit area per unit of time (Wm$^{-2}$). This is represented as

$$Q_f = Q_{fb} + Q_{fv} + Q_{fm}$$

where anthropogenic heat release from cities ($Q_f$) = Heat from electricity use and fuel combustion (industry) in buildings ($Q_{fb}$) + Fuel combustion heat from ground vehicles ($Q_{fv}$) + Heat from human and animal metabolism ($Q_{fm}$) [4]. According to a research done by Sailor and Lu (2004) [5], the contribution of human metabolism is relatively small (about 2–3% of the total anthropogenic heating profile). On the contrary motorized traffic and buildings- especially Heating, Ventilation, and Air Conditioning (HVAC) systems, release significantly higher levels of anthropogenic heat, making them crucial factors in estimating the impact of artificial waste heat released to the atmosphere.

2.2. Anthropogenic heat released from buildings
A significant revelation in these studies is that waste heat emitted from buildings is a by-product of the air-conditioning equipment used, which is an essential component in most of the upcoming mega-constructions in Colombo. According to Sailor (2011) [6], energy use in buildings for HVAC is a complicated function of occupancy, internal loads, and environmental loads, where the HVAC system manages internal thermal comfort during occupancy hours through heating and cooling systems. That is, heat transmitted into the building from the exterior environment ($E$) and internal heat generated by lighting ($L$), plug loads ($P$), and human metabolism ($M$) could cause the cooling system to consume additional energy ($AC$) to reject this heat to the outdoor environment. This heat rejection, $R$, can be represented as:

$$R = E + P + M + L + AC$$

This scenario is studied explicitly at building scale though the ‘building energy model’ approach, which determines the energy consumption within buildings and its relationship to HVAC equipment.
under given environmental conditions. According to research, this can be extended to estimate anthropogenic emissions from HVAC heat rejections by linking a detailed building energy model with an urban canopy meteorological model, for macro-scale estimations.

2.3. Anthropogenic heat released from vehicles
Traffic related anthropogenic heat is generally considered to be a difficult estimation and often evades systematic treatment, especially in developing countries where traffic intensity indicators are either not routinely recorded or not publicly available. The most challenging aspect is deriving a typical daily profile of the anthropogenic heat release rate, which is essential for the accuracy of the urban microclimate models. However, studies show that in the urban context, waste heat emission from combustion of gasoline and diesel fuels constitutes a significant source [7].

2.4. AHF as a part of the Urban Energy Budget model
This theory describes Earth’s surface layer energy reactions and lays a foundation to understand the Urban Boundary Layer climatology. It provides a fundamental understanding of how air, surface temperature, humidity, boundary layer depth, as well as concentration of pollutants behave. This is defined as

\[ \text{Urban Energy Budget: } Q^* + Q_F = Q_H + Q_E + Q_S, \ (\text{Wm}^{-2}) \]

In this equation, \( Q^* \) is net radiation, \( Q_F \) is anthropogenic heat flux, \( Q_H \) is turbulent sensible heat flux, \( Q_E \) is latent heat flux and \( Q_S \) is storage heat flux. This supports to estimate and determine the relationships between each component when studying the urban-rural energy balance differences [3].

2.5. Adopting inventory approaches to estimate AHF
Estimation of anthropogenic heat emissions is a challenge in developing countries since it requires extensive technological expertise and data inventories. Hence this study is based on energy consumption data gathered on utility/ energy consumption surveys which is spatially mapped to city-scale, along with land-use data. Energy statistics with usage/ activity and building typology are also considered in some research to calculate diurnal or hourly anthropogenic heat emissions that impact urban air temperatures. Research by Sailor (2011) [6] states that considering a controlled volume within a city allows to track all energy movement in and out of this controlled volume. Hence this approach can be used to conduct to evaluate the impact of AHF to the city of Colombo.

3. Method: calculating AHF for CCA
This research approach dwells upon utilizing the LCZ classification system to map the existing (2018) conditions and the development scenario under the CCADP for 2030, and thereby conclude the anthropogenic impact proportionately to its sources. This is based on literature that states more discernible changes in the CCA relates to land cover changes than building morphology, that land cover changes are more malleable to public policy initiatives, and are therefore more readily controlled by planners and designers [8].
The LCZ classification comprises of 17 zone types at the local scale (10^2 to 10^4 m), where each type is unique in its combination of surface structure, cover, and human activity. Classification of sites into appropriate LCZs requires basic metadata and surface characterization, which provides a standard framework for reporting and comparing field sites and their temperature observations [9].

To establish the research methodology as shown in ‘Figure 1’, selection of the CCA as a representative case study is supported by the understanding that it encompasses most of LCZs prevalent in Colombo’s urban context, as identified from the LCZ maps for Colombo Municipal Area developed by Perera et.al. (2015, 2018) [10] [11]. Quantitative values on electricity consumption within CCA is obtained from the Ceylon Electricity Board (CEB), while population and traffic counts within the study area for a selected time frame are taken from the Census of population and housing, Sri Lanka-2012 and Urban Transportation system development project for Colombo metropolitan region and
suburbs report (CoMTrans) [12] respectively. Electricity consumption data confirms Colombo to be the highest consumer which implies equal waste heat emission from buildings. The representative study area is thus narrowed to Colombo 2 since it shows a moderate composition of all building types. It is also based on the assumption that imminent CCADP developments will make most changes to building density and land use in this area by 2030.

Building Heat Emission (BHE) is calculated by considering electricity consumption and heat emission from HVAC systems according to averaged usage rates per building usage and scale, which is used to assign an average heat emission per building per day, for each LCZ class. Thus, anthropogenic heat released from buildings can be represented by the LCZ land use maps to show heat emission intensity in each LCZ. Vehicle and metabolic anthropogenic waste heat is calculated using existing survey data for the CCA, which are paired with proxy values supplied from literature. The AHF value range defined per LCZ class within the classification system is taken as an average to compare the actual values for Colombo with the international classification system. Percentages of each land use type and assigned building heat emission per LCZ is used to estimate the impact of AHF to CCA in 2030 to ascertain its impact at neighbourhood scale, and thereby to the UHI in Colombo City, as a repetitive cycle of energy use and heat release in cities.

Figure 1. Research Design.
Source: Author
4. Results and discussion

4.1. Land-use and building density changes
The form of the city is changing with development, especially with the ocean reclamation projects for the new Port and Port City projects. However, this study is more concerned with the changing morphology of the existing urban fabric and therefore, the impact of AHF. As given in ‘Figure 2’, comparison between the two LCZ maps with land cover fractions shows that Planning and Building regulations of the CCADP allows extensive developments, where most less-dense LCZs could morph into Compact High-rises (LCZ1).

As highlighted by Perera and Emmanuel (2018) [11], this has negative local warming consequences. Building scales show an increase, which implies a drastic increase in population inflow, vehicles and a denser building morphology. It should be noted, how even in 2018 the roads cover a significant proportion of the land cover, implying a large contribution of waste heat from vehicles to the total AHF in Colombo. The natural land cover does not show a significant variation.

4.2. Estimating anthropogenic heat emitted from buildings (Q_{Fb})

Figure 2. Comparison between LCZ maps for 2018 and 2035
Source: Author after Perera et al (2018)
According to research, it is possible to assume that energy consumed can be considered equal to the anthropogenic heat released to the atmosphere, regardless of thermal mass and energy efficiency in the electronic equipment used in that building \cite{13}\cite{14}\cite{15}. Thus, collected area-specific electricity consumption data is referred to select four main tariff categories: Domestic, GP1 (commercial- non A/C), GP 2 (large commercial buildings- A/C) and Industrial, based on their high representation of number of accounts, building type/ usage, scale and energy consumption.

An average energy consumption per building for a day from each tariff category is taken, and it is assumed that 70% of waste heat is emitted additionally to the average electricity consumption from the AC systems \cite{6} in relevant tariff categories. This value is calculated separately (Energy consumption by HVAC system (kWh) x COP value = waste heat emitted (joule)) \cite{16} and added to the 30% of waste energy consumed/ emitted by other electronic appliances \cite{6}. For non-A/C categories 100% of electricity consumption is assumed to convert to waste heat.

To match the energy consumption and physical attributes of buildings with the LCZ classification, an average heat emission per building day per each LCZ class is needed. Hence two sample blocks from each of the 8 LCZs identified in Colombo 02 study area from 2018 LCZ map, are selected to get an average benchmark value. The counts of buildings from each building type/ tariff category, per each sample block is considered to obtain a total anthropogenic heat emission from buildings (Q_{Fs}) for each LCZ block. Hence, Q_{Fs} of a particular block is equal to no. of buildings x benchmark value divided by maximum buildable area (actual lot area x built fraction as per regulations). A colour code is given to defined value ranges to spatially map BHE per LCZ block in the study area.

Results show that significant ranges are above 300 Wm\(^{-2}\) and between 100- 200 Wm\(^{-2}\). Hence the heat sources in areas marked by these ranges could be isolated for further information on aspects that affect the AHF intensity. Assuming that the study area represents BHE in CCA, an average value of 129 Wm\(^{-2}\) could be obtained as the anthropogenic heat emission from buildings in Colombo city. Thus, Q_{Fs} portrays a strong correlation between the benchmark values obtained from sample blocks for each LCZ class, the number of buildings per each block and the built fractions considered for each block. This corresponds well with the LCZ and AHF density value ranges presented in Stewart & Oke (2012) \cite{9}.

### 4.3. Projecting anthropogenic building heat emission to 2030.

Anthropogenic heat flux from buildings was projected for 2030 based on the LCZ class per block and built fraction defined in the CCADP.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Comparison of emitted waste heat intensity from buildings in 2018 and 2030 using assigned colour codes per heat range}
\label{fig:fig3}
\end{figure}

\textbf{Figure 3.} Comparison of emitted waste heat intensity from buildings in 2018 and 2030 using assigned colour codes per heat range

Source: Author

The average anthropogenic heat estimation taken from the building heat emissions in 2030 projections is 620 Wm\(^{-2}\), which is 4 times higher compared to 2018. Hence this change in land use and building scale could pose dire consequences for UHI mitigation and adaption.

### 4.4. Estimating anthropogenic heat from metabolism (Q_{Fm})

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The anthropogenic heat flux resulted from human metabolism is calculated based on the proxy scale: energy released per person (Mt) is 175W [13] [15]. According to residential population counts in census data, population density (PD) in CCA is 3417 persons/km², in a land extent of 37 sqkm. Thus, total metabolic heat (QFM), is calculated at a rough scale using the equation:

\[ Q_{FM} = \frac{(PD \times Mt \times Area)}{10^6} \]

Accordingly, the anthropogenic heat flux in CCA from human metabolism is 22 Wm⁻². However, a majority of day-time population in this area would ideally be from the working population who are daily commuters, rather than residents. Hence this value is an understatement of the actual QFM. With the CCADP, one of the major objectives is to zone and develop Colombo city for mixed-use, which increases both commercial and residential population, and therefore it will increase the contribution to AHF from metabolic heat.

4.5. Estimating anthropogenic heat from vehicles (QFv)

Vehicle heat emissions are calculated based on the average engine capacities and engine efficiencies of generalized vehicle types. The CoMTrans report [12] provides rough figures on vehicle counts that enter CCA boundary on a daily basis. As shown in Table 1, a one third efficiency is assumed for all engines, leaving a 0.66 inefficiency by which the heat emitted from the exhaust is calculated. Average distance travelled by a vehicle is taken as 15 km in general, and average speed for each vehicle type during peak traffic hours is considered to define a time frame when the engine would be running within CCA area. Thus, total waste heat emission per vehicle category was calculated, resulting in an average anthropogenic heat flux of 20 Wm⁻² within CCA, per day.

| Vehicle category | Vehicle count | Waste heat per vehicle - 0.66% from engine capacity (W) | Average speed in CCA at peak hours (km/h) | Average time taken to travel 15km within CCA (h) | Average heat emission from a vehicle (W/day) | Total waste heat emission per category (W) |
|------------------|---------------|----------------------------------------------------------|-------------------------------------------|---------------------------------------------|------------------------------------------|------------------------------------------|
| Motorcycle       | 137928        | 2237                                                     | 26                                        | 0.58                                        | 53.78                                    | 7417277                                  |
| Three-wheeler    | 132181        | 2217                                                     | 22                                        | 0.68                                        | 62.99                                    | 8325956                                  |
| Car, jeep        | 155169        | 74570                                                    | 21                                        | 0.71                                        | 2219.35                                  | 344373581                                |
| Passenger van    | 57470         | 64627                                                    | 21                                        | 0.71                                        | 1923.43                                  | 110539668                                |
| Pick             | 17241         | 74570                                                    | 22                                        | 0.68                                        | 2118.47                                  | 36524471                                 |
| Medium truck     | 40229         | 76459                                                    | 20                                        | 0.75                                        | 2389.35                                  | 96121044                                 |
| Large truck      | 5747          | 152968                                                   | 20                                        | 0.75                                        | 4780.25                                  | 27472084                                 |
| Container truck  | 2873.5        | 198853                                                   | 20                                        | 0.75                                        | 6214.17                                  | 17856408                                 |
| Minibus          | 2873.5        | 61147                                                    | 13                                        | 1.15                                        | 2939.78                                  | 8447455                                  |
| Bus              | 22988         | 86153                                                    | 13                                        | 1.15                                        | 4141.98                                  | 95215861                                 |
| Total waste heat emission from vehicles (W) | | | | | | 752293804 |
| Anthropogenic heat flux from vehicles (Wm⁻²) | | | | | | 20 |
Accordingly, a vehicle would be travelling for an average of 45 minutes within CCA, per day. However, hourly traffic data on vehicle counts, speeds and distances travelled by each vehicle would coincide with the AHF intensity on a finer scale. Accordingly, the rough estimation of total vehicle heat emission from roads is $752 \times 10^6$ W.

![Waste heat emission per vehicle type](image)

**Figure 4.** Comparison between factors affecting $Q_{fv}$

As shown in ‘Figure 4’, the waste heat emission from four-wheeled private vehicles appears to be the largest contributor to $Q_{fv}$, despite motorcycles and three-wheelers occupying the highest percentage in terms of vehicle count. This reflects the demographic factors and influence of GDP to the traffic volumes generated in the area. The trip purpose of a majority of vehicles on roads within Colombo city is returning home [12], which implies that the waste heat contribution is mainly from a certain category of users: those who can afford to travel to CCA daily using their private vehicles.

4.6. **Total anthropogenic heat emission in CCA- 2018**

Combining the values obtained for waste heat emitted from the three sources: Buildings, metabolism, and vehicles, a total anthropogenic heat of 171 Wm$^{-2}$. Accordingly, contribution from buildings ($Q_{fb}$) is 75%, vehicles ($Q_{fv}$) is 12% and metabolism ($Q_{fm}$) is 13%.

This value is an average scale as to what the anthropogenic heat flux is for Colombo city, for the year 2018. Assuming on the building scale changes as per regulations, population growth predictions and predicted traffic counts for 2030, the anthropogenic heat intensity could only be several times higher.

5. **Discussion and conclusions**

Impacts of anthropogenic heat can be considered as adverse results of urbanization, due to shortcomings in poorly assessed development proposals. UHI is an evident result of anthropogenic heat accumulation and is critical to the livability of cities, causing a loop of energy consumption and waste heat emission as a result and cause. Hence the objective of this study is to estimate the current impact of anthropogenic heat flux and emphasize the need to evaluate the scale of environmental impact before facilitating intense developments in future.

5.1. **AHF from metabolism**

Metabolic heat is significant in terms of internal heat gains of a building, which either causes discomfort (affecting indoor thermal comfort) or an addition to the cooling load if the building has an HVAC system. The latter is critical since it contributes to the total waste heat emission from a building, since BHE contributes to 75% to the AHF in Colombo. However, this study considers human
metabolic heat as a constant proxy value without hourly activity profiles and population variations, and it is estimated to the total land extent of CCA as suggested in literature. This gives an overestimation for metabolic heat, also since building and vehicle waste heat is more specifically addressed as to what percentage of land cover they occupy and their active time, respectively. Hence it could be assumed that $Q_{Fm}$ is negligible as suggested in literature and it should be calculated to a finer grain for a more accurate estimation.

5.2. AHF from vehicles
The highest heat emission is recorded from the “jeep/ car” category where both the vehicle count and engine capacity per vehicle is noticeably high. Waste heat emission from motorbike, three-wheeler and freight vehicle categories is low, where the smaller vehicles have small engine capacities despite large vehicle counts, while the freight vehicles have large engines despite a low vehicle count (See ‘Figure 4). Therefore, vehicle counts, engine efficiencies and time spent active (which is derived from differences in speed- Table 1.) in each vehicle category has a significant contribution to determine the waste heat emission.

Comparing vehicle ownership data and daily passenger counts [12] reveal that a majority of population uses private vehicles to daily travel to, and within CCA. Yet the disparity in heat emission lies within the same owner group portraying a large variety in vehicle category, which is mainly governed by user income category. This implies how vehicle size, passenger load capacity and level of maintenance have lower contribution to the heat emission from fuel combustion; the observation is drawn on the assumption that private vehicles for domestic use will have more maintenance facilities than freight vehicles or those used for public transportation such as buses. Since this calculation assumes that all vehicles are engine driven, the engine efficiency of each vehicle defined by the manufacturer has a considerable impact on anthropogenic emissions. With developments that promote transportation infrastructure, the number of vehicles could drastically increase, which makes it a key concern to either limit vehicles by policy or maintain a feasible standard to reduce emissions. Thus, policies to promote hybrid and electric vehicles could significantly reduce the contribution to AHF from vehicles, due to their high engine efficiency. However, vehicle emissions in this study do not include heat radiated from engines nor from the surface of the vehicle body. This implies that $Q_{Fv}$ should obtain a higher percentage than metabolic heat and that the parameters considered for this study could be improved in future studies for more precise calculations.

5.3. AHF from buildings
Built areas cover roughly 62% of total land extent in CCA, which roughly gives a total BHE of 2800x $10^6$ W. Thus being the largest contributor to AHF, buildings can determine the influence of anthropogenic emissions to the UHI effect that affects the climate in Colombo. Electricity consumption in buildings (including building type and the energy efficiency of electrical equipment used) is directly proportional to the cooling load of the HVAC system, which is directly proportional to the waste heat emission from a building. This is evident in the heat emission difference between AC and Non-AC buildings within the region. However, since the cooling equipment and their specific technologies as well as chiller efficiencies make a drastic impact to the total waste heat emission from a building, the optimum choice based on function, cooling load and budget should be selected despite other challenges.

Furthermore, this study proves that electricity consumption data can be combined with building density parameters and land cover data to derive an average BHE per LCZ class within a particular area. However, accuracy of the calculation relies heavily on parameters such as lot area per LCZ block, building types, electricity consumption and number of buildings, making it crucial to update the sample blocks when applying this method to a different context. In addition, further improvements should ideally incorporate the number of floors per building in each LCZ block, since plot coverage and number of buildings alone do not define the actual scale of a building, and since building heights show a drastic increase with 2030 CCADP regulations. The study portrays a possibility of 400%
increase in anthropogenic emissions from buildings. Hence, substantial UHI mitigation strategies should come from the building construction sector: to design more energy efficient buildings with passive lighting and ventilation strategies, or to use more efficient HVAC systems.

5.4. Impact at street scale

Street scale is relatable to humans since it defines a parameter to evaluate the urban micro climate within the canopy layer. AHF however, is typically studied at the urban boundary layer, extending to meso-scale models. Since this study was conducted using an inventory approach, impact at a micro-climate scale can be assumed using empirical perceptions on thermal comfort, which may vary with actual numeric values. Thus, the micro-climate would get an immediate impact from vehicles in traffic and metabolic heat from commuters since the heat emitted prevails at the screen level before getting dissipated by wind or reaching the boundary layer.

Emission of pollutants is also a crucial aspect that needs to be studied in detail, since it poses major impact on human health and urban climatology. Multiple research show that passive cooling technologies, green building techniques and even the set point temperature in an AC system can make massive impacts to the heat gains and emissions of buildings. Hence serious attention should be paid to how waste heat is released to the environment since cooling towers, exhaust fans and AC outdoor units record high air temperatures around them, which accumulates at screen level. AHF affects the urban boundary layer where the pollutants and heat contribute to the atmospheric temperature. This is strongly linked with the UHI phenomenon that affects the micro-climate by increasing the air temperature, which affects all living and non-living entities that absorb and release heat in return.

5.5. Impact at city scale

The calculations show a direct relationship between the building density, building type and size of the considered plot for calculation. Land use and building density are not the sole governing aspects that determine anthropogenic heat released from buildings in an area. Also, when considering the city scale, vehicle emissions are significant since streets occupy almost 29% of land cover as discovered from the LCZ analysis for 2018. Thus, UHI mitigation strategies should consider all aspects of anthropogenic heat emissions for a sustainable development.

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