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Research Article

A Unified Analytical Assessment of Ground Clearance Effects on the Aerodynamic Loading of Tandem Tilted Flat Plates

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ABSTRACT

The interaction of flow, wake development and aerodynamic loading of tandem aerodynamic configurations are highly affected by ground-effect aerodynamics. Many experimental and computational studies have studied these phenomena, but most are selected investigation and presented as separate performance parameters which offer limited support for integrated engineering interpretation. This study proposes an analytical methodological framework that is transferable, called the Unified Ground Clearance Assessment Framework (UGCAF), which is derived from recent developments in the field of systematic reinterpretation of existing research data. Instead of obtaining new aerodynamic data, UGCAF itself systematically reorganizes and assesses the validated selected investigation based on five complimentary engineering indicators: Aerodynamic Loading, Ground-Clearance Influence, Wake Interaction Strength, Shielding Behaviour and Comparative Performance Rating. It is illustrated by a typical published experimental study of tandem tilted flat plates under various ground-clearance conditions. The aerodynamic loading is predicted to be dominated by the coupled effect of the plate position, wake development, and ground effect, and an increase of the ground clearance is expected to shift the downstream plates towards more wake redevelopment and reduced aerodynamic shielding, and enhance loading recovery of the downstream plates compared to the leading plate. UGCAF allows to combine several aerodynamic mechanisms in a consistent engineering approach to the analysis of published aerodynamic measurements and to provide a comparative assessment between validated experimental and computational studies. The proposed framework is not dependent on the data acquisition methodology, and is a portable engineering tool for the interpretation of aerodynamics behaviour for multi-body aerodynamic systems (such as ground-effect systems).

1. INTRODUCTION

Aerodynamic loading is one of the most important factors which determine the safety and performance of engineering structures under wind environments and their durability. Aerodynamics, boundary layers and the geometry of structures are complex and create aerodynamic forces on ground mounted photovoltaic (PV) arrays, highway noise barriers, lightweight roof systems, protective barriers and other bluff body structures. These interactions create flow separation, vortex shedding, wake interference and pressure redistribution which have a significant effect on the aerodynamic loads acting on the structures and can lead to increased structural deformation, structural fatigue and maintenance needs [1].
Tilted flat plates in tandem are one of the simple geometries widely used in wind engineering studies and have proven to be a good model for the study of the aerodynamic behaviour of bluff-body configurations. This kind of set-up is a realistic approximation of many practical engineering applications, especially in the case of ground-based PV arrays comprising a series of inclined panels with a comparatively small distance in between them above the ground. Tandem configurations, in contrast to isolated plates, produce robust interactions of wakes between adjacent plates, which cause aerodynamic shielding, wake recovery and non-uniform drag distribution across the plate array. Therefore, the aerodynamic loading on each of the plates downstream is not only a function of the wind speed and direction over the inlet, but also dependent upon the disturbed flow created by the upstream plates [2-6].
A number of geometric and flow parameters such as the inclination angle, plate spacing, aspect ratio, Reynolds number, wind direction, and ground clearance have been shown to be important aerodynamic loading parameters in tandem flat-plate systems. One of these parameters is particularly important since it directly affects the growth of the boundary layer

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close to the ground and alters the flow underneath the plates in the underbody. The aerodynamic drag force between plates and for the tandem configuration can change significantly if the clearance ratio is varied, due to changes in the pressure force distribution, flow recirculation and wake interaction effects [7-10].
Measurements from experimental wind-tunnel studies have been very helpful in the determination of drag coefficients, pressure distributions, and wake characteristics under various configurations, and detailed visualization of the flow using computational fluid dynamics (CFD) has been useful in understanding the flow physics underlying the drag behavior. All such studies show highly nonlinear aerodynamic behaviour of tandem loading due to the interaction of incoming airflow and successive wake structures, and the necessity of accurate assessment of these loads for the engineering design and optimization process. [11, 12]
At the same time as the ongoing development of experimental and computational aerodynamic investigations, recent methodological studies have stressed the potential for useful scientific work to be generated from the systematic reinterpretation of validated published data using transferable analytical frameworks. These methods do not create new experimental observations, instead they summarise, compare and synthesize the results of previous studies, giving common sense engineering explanations and enabling consistent engineering decisions to be made between related studies. These systems fill the gap between independently published measurements and computational modelling, and provide a unified analytical understanding of these observations. Although significant progress has been made in methodological research, similar, analytical approaches have not been widely studied in wind engineering and ground-effect aerodynamics where published aerodynamic results are still largely presented as isolated performance parameters rather than as elements of an integrated engineering assessment [13].
While a number of studies have significantly enhanced the knowledge of aerodynamic loading on tandem tilted flat plates, the results are typically presented in the form of aerodynamic quantities for each of the experimental conditions. Most of the studies report drag coefficient only or pressure coefficient only, but not combine these aerodynamic parameters into an engineering evaluation. Engineers have to use many independent figures and data sets to get a general idea of the aerodynamic characteristics of a specific configuration, so it is common for them to have to use several sets of data. Moreover, efforts have been minimal to build a single analytical method that allow a simultaneous analysis and evaluation of aerodynamic loading distribution, shielding behaviour, ground-clearance sensitivity and the aerodynamic response of tandem plate systems in a unified assessment framework [14,15].
Based on these challenges, the present study offers the Unified Ground Clearance Assessment Framework (UGCAF). Instead of focusing on the drag coefficient alone as an aerodynamic parameter, UGCAF presents a transferable analytical methodology for the systematic rearrangement of selected investigation into a single engineering assessment. This study's key contribution is the development of UGCAF, a methodological framework that can be used systematically to interpret published aerodynamic datasets. The framework contributes with:

1. Introducing a standardized methodological framework for aerodynamic interpretation.
2. Integrating five engineering indicators into a unified analytical assessment.
3. Providing a reproducible methodology for evaluating ground-clearance effects using selected investigation.
4. Supporting engineering decision-making through standardized interpretation of validated aerodynamic datasets

2. RELATED WORK

The aerodynamic behaviour of bluff-body structures has been a topic of great interest and its direct effect on structural safety, stability and aerodynamics of engineering systems subjected to wind loading. The tilted flat plate is one of the simple bluff-body shapes that has received much attention as a model for the study of the aerodynamic phenomena of boundary-layer separation, vortex shedding, wake formation, and pressure redistribution, among others. The simplified configurations closely resemble many practical applications such as ground mounted photovoltaic (PV) arrays, light roofing systems, wind barriers and other structures close to the ground, enabling researchers to study the effect of individual geometric and flow variables under well-controlled conditions [16-18].
The aerodynamic loading on inclined flat plates has previously been shown to be highly dependent on inclination angle, Reynolds number, wind turbulence at incidence and geometry of the structure. The changes in the value of inclination angle change the flow separation location, the pressure distribution around the plate and greatly influence the wake development and thus the aerodynamic drag change is nonlinear. Previous experiments conducted in a wind tunnel and numerical calculations (computational fluid dynamics, or CFD) have shown that the aerodynamic loading of medium inclination angles is typically the most sensitive to wake interaction and vortex formation [19]. While these investigations have contributed greatly to the understanding of bluff-body aerodynamics, the majority are based on isolated flat plates, and neglect the aerodynamic interference between neighbouring structures.
Further studies were conducted after the initial studies of isolated plates to simulate practical engineering systems by extending the analysis to tandem and multiple-plate configurations. In tandem configurations, aerodynamic interference is more complicated as the downstream plate is always subjected to the disturbed flow field created by the upstream plate.

This interaction leads to aerodynamic shielding, wake recovery, drag redistribution, and substantial drag modulations between consecutive plates. These interference effects are more complex as they are influenced by the several geometric parameters such as longitudinal spacing, inclination angle, aspect ratio and wind direction in the case of isolated geometries [20] compared to the aerodynamic prediction.

Ground clearance is one of the most influential geometric parameters that controls the aerodynamic behaviour of tandem configurations. The gap between the structure and the ground affects the atmospheric boundary layer development, the flow under the structure and the interaction between separated shear layers and the downstream wake structure. Experimental investigations have shown that aerodynamic drag, pressure recovery and wake interactions change significantly, even for a relatively small change in the clearance ratio, especially for the downstream plates in which wake interaction plays the dominant role. Numerical studies have also shown that the ground clearance not only affects aerodynamic force magnitudes but also the flow topology around tandem configurations [21].

The understanding of aerodynamic loading mechanisms in tandem bluff-body systems has been greatly advanced with recent experimental measurements and CFD techniques. The high resolution of the numerical simulations has allowed a detailed visualization of recirculation regions, turbulent kinetic energy, pressure fields and vortex structures that are hard to measure experimentally. Likewise, wind tunnel tests have yielded satisfactory aerodynamic data for different inclination angles, spacing ratios and clearance conditions. These studies have helped to optimize the aerodynamics of an photovoltaic array and other ground mounted engineering structures. However, most of the published investigations still report the aerodynamic data as separate variables like drag coefficients, pressure coefficients, etc. or local pressure distribution for a certain experimental setup [22].

The current body of knowledge has greatly increased in understanding the aerodynamic loading on tandem tilted flat plates, but one aspect is still missing. Most of the earlier studies have assessed the aerodynamic parameters by themselves and inadequate efforts have been made to incorporate these parameters into an overall engineering assessment. Thus, the engineer often has to draw his own conclusions from many of these figures, pressure contours, drag characteristics, and experimental observations on the overall aerodynamic performance of a particular configuration. This disjointed presentation makes it difficult to make direct comparisons between the various geometric arrangements and restricts engineering application of published data sets, especially when several parameters concurrently affect aerodynamic behavior [23].

In addition, relatively little research effort has been directed toward the development of a general analytical tool that can provide a comprehensive assessment of the aerodynamic loading distribution, shielding efficiency, ground-clearance sensitivity and overall aerodynamic response of tandem plate configurations. Consequently, there is no systematic methodology developed in the literature to convert the traditional aerodynamic measurements to an integrated engineering assessment, which is applicable to comparative analysis and design optimization [24].

From the above review, it is clear that lack of aerodynamic data is not the big issue but the lack of a single analytical methodology for integrating various aerodynamic performance indicators in a comprehensive engineering assessment. Based on this, the present study suggests a Unified Analytical Assessment Framework which can be used to assess the aerodynamic loading on tandem tilted flat plates due to ground clearance. The proposed framework does not regard aerodynamic drag as the only aerodynamic performance parameter, but integrates various complementary aerodynamic performance indicators in order to systematically analyse aerodynamic loading, aerodynamic shielding, load redistribution and clearance sensitivity. The overall goal of this unified approach is the enhancement of the engineering interpretation of published aerodynamic data and to deliver a general analytical methodology, applicable to ground mounted bluff-body systems.

TABLE I. COMPARATIVE SUMMARY OF PREVIOUS STUDIES ON AERODYNAMIC LOADING OF TILTED FLAT PLATES

Configuration	Method	Main Findings	Limitation
Single tilted flat plate	Experimental	Influence of inclination angle on aerodynamic loading	No aerodynamic interference considered
Single flat plate	Experimental / CFD	Pressure distribution and drag prediction	Ground clearance not comprehensively analysed
Tandem tilted plates	Experimental	Wake interaction and aerodynamic shielding	No unified analytical evaluation
Near-ground structures	Experimental / Numerical	Significant influence of ground clearance	Individual aerodynamic parameters only
Photovoltaic arrays	CFD / Wind tunnel	Aerodynamic optimisation of PV systems	Limited comparative assessment
Bluff-body configurations	Experimental / Numerical	Comprehensive aerodynamic datasets	Absence of an integrated analytical framework

Previous research has focused primarily on studying individual aerodynamic parameters for specific experimental and/or numerical conditions, as indicated in Table I. None of the above investigations offers a general analysis framework that considers all three aspects of aerodynamic loading distribution, shielding behaviour, and ground-clearance sensitivity. This restriction is the motivation of developing the unified analytical assessment proposed in this study.

3. PROPOSED UNIFIED GROUND CLEARANCE ASSESSMENT FRAMEWORK (UGCAF)

3.1. Framework Overview

There exists a gap in the knowledge regarding the effect of ground clearance on the aerodynamic loading of tandem tilted flat plates, which is addressed by proposing the Unified Ground Clearance Assessment Framework (UGCAF), a generalized analytical methodology to systematically evaluate the effect of ground clearance on the aerodynamic loading of tandem tilted flat plates. UGCAF is based on the simultaneous consideration of several complementary performance indicators, which allows for comparison of the various geometric configurations and interpretation of the aerodynamic behaviour in a more comprehensive engineering sense.

The framework is developed to convert the traditional aerodynamic parameters into standardized performance parameters that are objectively able to represent the aerodynamic response of tandem flat-plate systems. The analytical procedure is made up of four steps: (i) aerodynamic data collection from experimental and/or numerical validations, (ii) standardization of the aerodynamic data in order to have a common reference for comparison, (iii) identification of common aerodynamic performance indicators, and (iv) comparative analysis for engineering evaluation. This process has been designed to reduce inconsistencies that arise in isolated parameter analysis and offers a structured method for assessing the aerodynamic effect of ground clearance.

The proposed UGCAF architecture is presented in overall architecture of the UGCAF shown in Fig. 1. The framework brings together aerodynamic data acquisition, pre-processing, indicator generation and comparative evaluation in one analytical process as shown. The proposed methodology is sufficiently general to be extended to other configurations near the ground which exhibit bluff-body aerodynamics, such as tandem tilted flat plates. Each step of UGCAF is described in detail in the following subsections, including aerodynamic indicators selected, evaluation procedure proposed, and comparative assessment strategy used during this study.

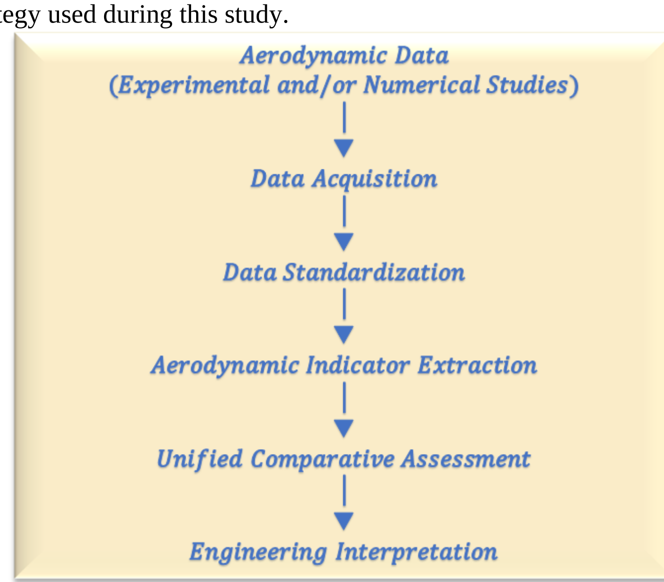

Fig. 1. Overall architecture of the proposed Unified Ground Clearance Assessment Framework (UGCAF).

3.2. Aerodynamic Input Parameters

The proposed Unified Ground Clearance Assessment Framework (UGCAF) is based on the synergistic combination of aerodynamic parameters and engineering assessment indicators to assess the aerodynamic behaviour of tandem tilted flat plates. The aerodynamic parameters are a set of physical properties of the flow and of the geometry, while the assessment indicators are a structured methodology for interpreting the aerodynamic performance under different ground-clearance conditions. This separation allows UGCAF to eliminate the need for the use of unconnected aerodynamic quantities and to replace them with a single engineering evaluation.

The aerodynamic parameters used in this study were chosen because they have been consistently reported in experimental and numerical studies of the aerodynamics of bluff bodies and are directly related to the aerodynamic loading on tandem flat-plate systems [25]. They define the physical structure of the framework and serve as an input variable for comparison with other systems in the future. To make the reader better understand the aerodynamic variables that were taken into account all throughout the proposed framework.

TABLE II. AERODYNAMIC PARAMETERS USED IN THE PROPOSED UGCAF FRAMEWORK.

Symbol	Parameter	Physical Significance	Role in UGCAF
(C_D)	Drag coefficient	Aerodynamic resistance	Primary aerodynamic input
$\left(\frac{H}{L}\right)$	Ground clearance ratio	Relative clearance	Ground-clearance characterization
$\left(\frac{S}{L}\right)$	Plate spacing ratio	Relative plate spacing	Wake interaction characterization
(θ)	Tilt angle	Plate orientation	Geometric configuration
$(C_p)(\boldsymbol{if\ available})$	Pressure coefficient	Surface pressure distribution	Flow interpretation
Wake characteristics	Wake behaviour	Flow interaction	Qualitative aerodynamic interpretation

The aerodynamic and geometric parameters of the tandem plate system are described by these parameters as presented in Table II. But individual parameters are not enough to evaluate aero performance. To this end, UGCAF presents a collection of engineering assessment indicators which group these variables into a coherent analytical assessment.

The assessment indicators are not new aerodynamic coefficients, but rather measurable quantities that reflect the aerodynamic characteristics. Rather they are the analytical criteria that UGCAF has used to understand the aerodynamic response overall for a given configuration. These indicators can be used to perform comparative engineering analysis but do not change the original aerodynamic data presented in previous investigations

TABLE III. ENGINEERING ASSESSMENT INDICATORS ADOPTED BY UGCAF.

Assessment Indicator	Purpose
Aerodynamic Loading Level	Evaluates the overall aerodynamic resistance of a configuration.
Ground Clearance Influence	Assesses the sensitivity of aerodynamic behaviour to variations in ground clearance.
Wake Interaction Strength	Evaluates the aerodynamic interference between upstream and downstream plates.
Shielding Behaviour	Assesses the effectiveness of aerodynamic shielding within tandem configurations.
Comparative Performance Rating	Provides an integrated engineering comparison among different configurations.

Table III shows how proposed indicators provide the analytical foundation of UGCAF to transform the traditional aerodynamic observations into the structured engineering evaluation. These are then used in the integrated evaluation process outlined in the next section to systematically evaluate the aerodynamic performance in various ground clearance situations.

3.3. Engineering Assessment Indicators

The proposed Unified Ground Clearance Assessment Framework (UGCAF) is a tool that provides a set of engineering assessment indicators that can be used to systematically interpret the aerodynamic behaviour of tandem tilted flat-plate configurations. The engineering assessment indicators offer the analytical process by which the aerodynamic input parameters are interpreted in a coherent engineering framework, as opposed to the aerodynamic input parameters that are measurable physical quantities that can be determined from experiments or simulations.

The indicators were chosen to be representative of the main aerodynamic phenomena affecting the ground-effect phenomenon in tandem configuration. UGCAF does not add any new aerodynamic coefficient parameters nor does it change the original published aerodynamic measurements, but it uses these indicators to structure and standardize the validated aerodynamic observations into a standardized analytical evaluation. This allows different aerodynamic configurations to be investigated with similar engineering principles and maintaining the same physical meaning of the original datasets.

TABLE IV. ENGINEERING ASSESSMENT INDICATORS ADOPTED IN UGCAF

Assessment Indicator	Purpose
Aerodynamic Loading Level	Evaluates the overall aerodynamic resistance of a configuration.
Ground Clearance Influence	Assesses the sensitivity of aerodynamic behaviour to variations in ground clearance.
Wake Interaction Strength	Evaluates the aerodynamic interference between upstream and downstream plates.
Shielding Behaviour	Assesses the effectiveness of aerodynamic shielding within tandem configurations.
Comparative Performance Rating	Provides an integrated engineering comparison among different configurations.

Each indicator is one of the complementary aspects of the aerodynamic response as presented in Table IV. Together, these indicators provide the analytical basis for UGCAF, helping to transform traditional aerodynamic observations into a system of structural engineering analyses that can be compared. The following section describes the methodology to assess each indicator.

3.4. UGCAF Assessment Criteria

The proposed Unified Ground Clearance Assessment Framework (UGCAF) has established a set of pre-defined engineering assessment criteria to interpret published aerodynamic measurements in a consistent, transparent and reproducible manner. All assessment indicators are based on aerodynamic characteristics from the source study, rather than engineering judgment. The criteria set an analytical standard procedure for selected investigation that turns the results into uniform engineering interpretation and support the use of framework on different validated aerodynamic datasets.

TABLE V. UGCAF ENGINEERING ASSESSMENT CRITERIA

Engineering Indicator	Assessment Basis	Published Aerodynamic Evidence	Engineering Objective
Aerodynamic Loading	Distribution of aerodynamic loading among tandem plates	Drag coefficient and pressure distribution	Identify critical loading regions and force redistribution
Ground-Clearance Influence	Variation in aerodynamic loading with changing ground clearance	Differences between ground-clearance configurations	Evaluate sensitivity to ground-effect conditions
Wake Interaction Strength	Recovery of aerodynamic loading along downstream plates	Wake-induced loading redistribution	Assess wake redevelopment and downstream flow evolution
Shielding Behaviour	Reduction of downstream loading caused by upstream plates	Relative aerodynamic loading reduction	Quantify aerodynamic protection between tandem plates
Comparative Performance Rating	Integrated assessment of all engineering indicators	Combined analytical evaluation	Produce an overall engineering assessment of the aerodynamic configuration

The aerodynamic evidence is used to assess each engineering assessment indicator in succession in the UGCAF assessment. The aerodynamic behaviour is then comprehensively interpreted in terms of the individual indicator evaluations. This standardised method allows a consistent, transparent, repeatable comparison of various aerodynamical configurations and allows to interpret published aerodynamic data in a consistent way.

3.5. UGCAF Evaluation Workflow

The proposed Unified Ground Clearance Assessment Framework (UGCAF) carries out the aerodynamic assessment with a structured analytical process. The framework aims to convert the different aerodynamic observations reported in the previous studies into a single engineering assessment so as to provide objective and consistent comparison between various tandem tilted flat-plate configurations with different ground clearances.

The evaluation is structured by UGCAF in a series of analytical steps rather than just analysing individual aerodynamic quantities as done in conventional comparative analysis. The aerodynamic parameters are first measured and normalized with respect to the standard engineering assessment indicators, and then finally treated as a complete comparative assessment. The methodology is structured in such a way that each configuration investigated is compared by the same analytical criteria, so that the comparison of aerodynamic analysis is more consistent, repeatable and transparent.

There are six sequential stages in the proposed evaluation procedure. The first step is to gather and validate published aerodynamic datasets and then extract the necessary aerodynamic parameters. The values of these parameters are then used to interpret the engineering assessment indicators outlined in Section 3.3. Finally, comparative evaluation and engineering interpretation is performed to find influence of ground clearance on aerodynamic loading characteristics of tandem tilted flat plates. Figure 2 shows the entire operational process of the proposed framework.

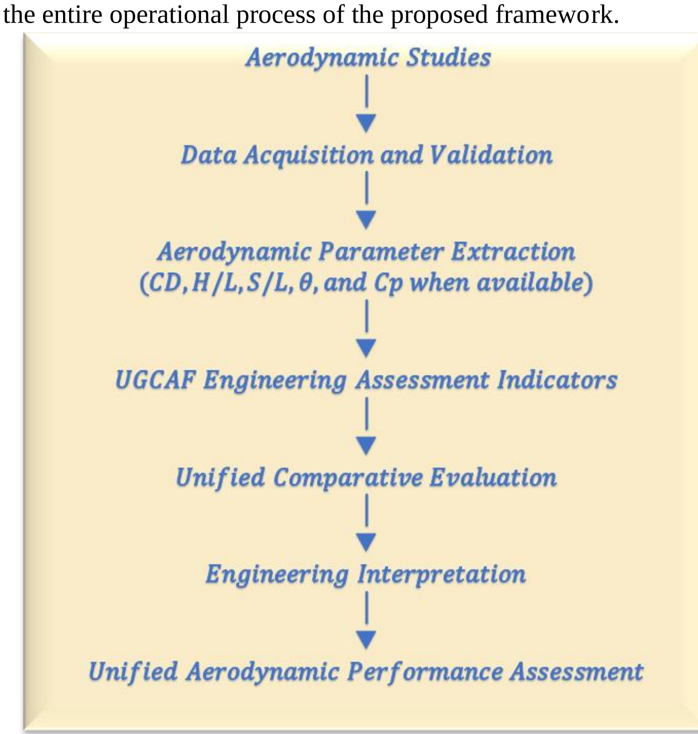

Fig. 2. Operational workflow of the proposed UGCAF framework.

The logical structure of UGCAF is shown in figure 2. The framework does not just arrange aerodynamic variables, but it also provides a systematic link between measured aerodynamic variables, engineering assessment indicators, comparative evaluation and engineering interpretation. Therefore, the aerodynamic data from various published sources can be compared to each other by applying a common analytical approach, and the original physical meaning can be maintained. In the following, the operational implementation of the UGCAF is summarized and outlined in Algorithm 1, after the overall workflow is defined.

Algorithm 1. Operational Procedure of UGCAF

Input:
Published aerodynamic datasets describing tandem tilted flat-plate configurations.
Output:
Unified comparative aerodynamic assessment.
1. Collect published aerodynamic datasets from experimental and numerical studies.
2. Validate the completeness and consistency of the collected datasets.
3. Extract the required aerodynamic parameters:
   • Drag coefficient (CD)
   • Ground clearance ratio (H/L)
   • Plate spacing ratio (S/L)
   • Tilt angle (θ)
   • Pressure coefficient (Cp), whenever available.
4. Standardize the extracted parameters to establish a common analytical basis for comparison.
5. Evaluate each configuration using the UGCAF engineering assessment indicators.
6. Perform unified comparative analysis among all investigated configurations under identical evaluation criteria.
7. Interpret the aerodynamic influence of ground clearance and identify dominant aerodynamic performance trends.
8. Produce a unified comparative aerodynamic assessment together with an engineering interpretation of the obtained results.
Return: UGCAF comparative aerodynamic assessment.

The suggested assessment process provides a clear analytical flow from aerodynamic measurements towards engineering interpretation. The UGCAF concept introduces a new approach for separating the data acquisition, parameter standardization, engineering evaluation, comparative analysis, and final interpretation to reduce the subjective interpretation of the results, and enhances the uniformity and repeatability of comparative aerodynamic evaluations by applying the same analytic criteria on all the configurations investigated.

Moreover, the framework does not change or re-evaluate the existing experimental or numerical findings that have been published in the literature. Rather, UGCAF offers a common approach to analyzing investigation through a common framework of engineering assessment indicators. In this way, it is possible to make a meaningful comparison between studies which have been performed with different experimental conditions and to retain the physical meaning of the original aerodynamic measurements. Therefore, UGCAF is not considered as a new aerodynamic prediction model, but rather as a framework for analyzing and supporting decision making.

The methodology presented in this section is the basis of the application of UGCAF in the next section. The following example illustrates the use of the proposed framework for analysing published aerodynamic datasets and the effect of ground clearance on the aerodynamic loading characteristics of tandem tilted flat plates.

4. IMPLEMENTATION AND ANALYTICAL APPLICATION OF THE PROPOSED UGCAF FRAMEWORK

A representative published aerodynamic investigation was selected and applied to the proposed Unified Ground Clearance Assessment Framework (UGCAF) to illustrate how it can be implemented and perform analysis. The aerodynamic measurements reported in this study have been obtained from the selected investigation, but the contribution towards the present work is not to reproduce or resume the results of the report. UGCAF, however, utilizes a single analytical approach that re-organizes, assesses and makes a systematic interpretation of selected investigation based on a unified engineering assessment framework.

The first investigation mainly addressed the aerodynamic characteristics of tandem tilted flat plates under various ground clearance conditions in terms of the drag coefficient, geometric ratios, and the observations of the pressure. These measurements are correct for the aerodynamics of an individual configuration but are not one engineering measurement that can assess the aerodynamic loading, ground-clearance influence, wake interaction, shielding behaviour and overall comparative performance.

UGCAF overcomes this limitation by using the same engineering assessment criteria for all the configurations studied in the selected configuration. Each ground clearance case is thus considered separately as an aerodynamic assessment case and is judged based on the five engineering assessment indicators set up in Section 3.3:

1. Aerodynamic Loading Level

2. Ground-Clearance Influence
3. Wake Interaction Strength
4. Shielding Behaviour
5. Comparative Performance Rating

This analytical process allows to convert the original aerodynamic measurements into a one-dimensional comparative evaluation that is always capable of explaining the interactions between ground clearance, aerodynamic loading, wake interaction and shielding behaviour. The scientific value of UGCAF is thus the development of a common framework for analysis of published aerodynamic data and not the creation of new experimental or numerical data. The process of implementing UGCAF has four steps:

1. Extraction of the reported aerodynamic parameters;
2. Organization and standardization of the investigated configurations;
3. Evaluation using the UGCAF engineering assessment indicators; and
4. Synthesis of the individual engineering evaluations into a unified engineering interpretation.

The complete analytical workflow adopted by the proposed framework is illustrated in Figure 3**.**

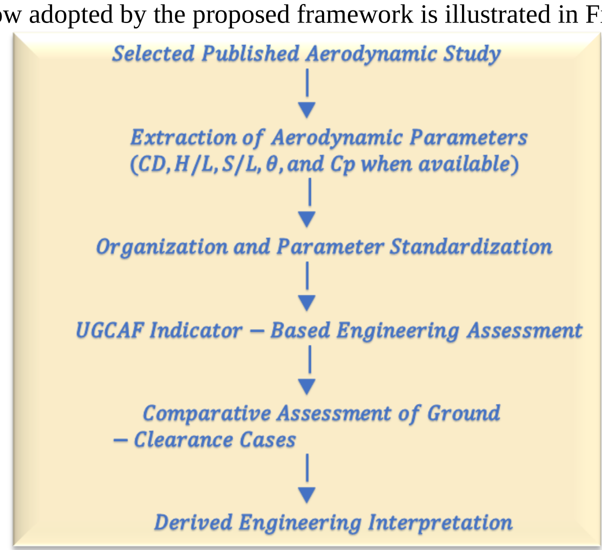

Fig. 3. UGCAF-Based Analytical Workflow Applied to the Selected Published Aerodynamic Study

In addition, Figure 3 shows the process of UGCAF to conduct a comprehensive analysis of the selected published investigation. Instead of changing the aerodynamic data reported, the framework follows a sequence of extracting the parameters, engineering normalization of parameters, indicator-based evaluation, comparative evaluation, and finally engineering interpretation. This means that all investigated configurations are treated according to similar engineering criteria, resulting in consistency, transparency and repeatability of the analytical process.

TABLE V. COMPARISON BETWEEN THE ORIGINAL PUBLISHED INVESTIGATION AND THE PROPOSED UGCAF FRAMEWORK

Assessment Aspect	Original Published Investigation	Proposed UGCAF Framework
Primary objective	Measurement or numerical prediction of aerodynamic behaviour	Unified analytical assessment of published aerodynamic behaviour
Data source	Original experimental or numerical results	Published aerodynamic data extracted from the selected study
Aerodynamic variables	(C_D), $\left(\frac{H}{L}\right)$, $\left(\frac{S}{L}\right)$, (θ), and (C_p) (when available)	The same variables analysed within a unified engineering framework
Ground-clearance evaluation	Direct presentation of aerodynamic variations	Systematic assessment of ground-clearance influence using unified indicators
Wake interaction	Described through individual aerodynamic observations	Evaluated using a dedicated engineering assessment indicator
Shielding behaviour	Indirectly reflected in the aerodynamic response	Explicitly interpreted as part of the unified assessment
Configuration comparison	Individual comparison of reported aerodynamic quantities	Integrated comparison using the five UGCAF engineering assessment indicators
Final outcome	Aerodynamic measurements and configuration-specific observations	Unified analytical organization, indicator-based assessment, and engineering interpretation of the published dataset

Table V shows the key difference between the initial aerodynamic study and the work of the current project. While the aerodynamic measurements are still the same as before publication in the investigation, UGCAF presents a new analytical methodology to rearrange these measurements into a common engineering assessment. Thus, originality of the present study is not based on the generation of new aerodynamic data but on the proposed analytical framework.

The aerodynamic parameters obtained from the published study are extracted for every ground-clearance condition investigated, and then standardized to form an analytical basis for the comparison. Each aerodynamic assessment case is then assessed with the five UGCAF engineering assessment indicators and then compared objectively and consistently to all of the assessed configurations. The effect of ground clearance on aerodynamic loading, wake interaction, shielding behaviour and overall aerodynamic response can be understood and interpreted in this procedure within a single engineering framework.

This section, however, does not simply give drag coefficients or pressure distributions but provides an analytical evaluation. Rather, it offers a systematic engineering interpretation of the relations between ground clearance, aerodynamical loading, wake interaction and shielding behaviour for the considered configurations. Thus, only the aerodynamic data used in the selected published investigation are used, UGCAF being the main methodological contribution for the present research. This subsection outlines the process of extracting of published aerodynamic data and the definition of the aerodynamic assessment cases for implementing the proposed UGCAF framework.

4.1 UGCAF Indicator-Based Assessment

After aerodynamic assessment cases preparation as described in Section 4.1, the proposed Unified Ground Clearance Assessment Framework (UGCAF) is adopted to make a standardized engineering assessment of all the investigated configurations. The original experimental investigation is reported in a series of aerodynamic measurements that are taken individually, whereas UGCAF has a unified analytical procedure that performs the same series of engineering evaluations on each aerodynamic assessment case. This standardisation allows for the objective comparison of the various ground clearance conditions, while maintaining the integrity and physical meaning of the chosen investigation.

The implementation begins by extracting the reported aerodynamic variables, including the drag coefficient $\left((C_D)\right)$, pressure coefficient $\left((C_p)\right)$, ground-clearance ratio $\left(\left(\frac{H}{L}\right)\right)$, plate inclination angle$\left((\theta)\right)$, and position of the plate in the tandem configuration Before the assessment process, these variables are then standardized to allow all aerodynamic assessment cases to be assessed by the same engineering criteria. For each aerodynamic assessment case, the sequential implementation procedure is summarized in Table VI.

TABLE VI. SEQUENTIAL IMPLEMENTATION PROCEDURE OF UGCAF

Step	Input	UGCAF Operation	Output
1	Published aerodynamic measurements	Extract aerodynamic variables	Standardized aerodynamic dataset
2	Standardized dataset	Evaluate Aerodynamic Loading Level	Loading assessment
3	Standardized dataset	Evaluate Ground-Clearance Influence	Ground-clearance assessment
4	Standardized dataset	Evaluate Wake Interaction Strength	Wake assessment
5	Standardized dataset	Evaluate Shielding Behaviour	Shielding assessment
6	Previous engineering assessments	Generate Comparative Performance Rating	Unified engineering assessment

Algorithm 2. UGCAF Indicator-Based Assessment

```
Input: Published aerodynamic dataset
Output: Unified engineering assessment
Begin
Load aerodynamic dataset
Extract aerodynamic variables
Standardize aerodynamic variables
For each aerodynamic assessment case do
   Evaluate Aerodynamic Loading Level
   Evaluate Ground-Clearance Influence
   Evaluate Wake Interaction Strength
   Evaluate Shielding Behaviour
   Integrate the engineering assessment results
   Generate Comparative Performance Rating
End For
Generate unified engineering interpretation
Return unified engineering assessment
End
```

Each aerodynamic assessment case is then assessed by the 5 engineering assessment indicators described in Section 3.3. The Aerodynamic Loading Level is calculated using the drag coefficient, changes in the ground-clearance ratio are analysed to determine Ground-Clearance Influence, aerodynamic interference between successive plates is interpreted to evaluate Wake Interaction Strength, and the drag-force and pressure are combined to evaluate Shielding Behaviour. Last, results of all these engineering evaluations are combined together to yield the Comparative Performance Rating, which gives a single engineering assessment of the aerodynamic performance of each configuration investigated.

The above implementation procedure forms a key part of the operational core of UGCAF. The framework is applied in the same way for all aerodynamic assessment cases, which guarantees the methodical consistency, reproducibility, transparency, and objective comparison of all the investigated configuration cases. From the engineering assessments, the analytical framework for the unified engineering assessment is developed in the following subsection.

4.2 Unified Engineering Interpretation

The proposed Unified Ground Clearance Assessment Framework (UGCAF) will enable the aerodynamic measurements, which have been extracted, to be converted to a unified engineering assessment for direct and objective comparison of the various tandem tilted flat-plate configurations investigated. The framework is not intended to deal with drag-force or with pressure measurement separately, but rather combines all aerodynamic aspects in a single analysis which allows for a comprehensive engineering interpretation of the aerodynamic behavior for different ground-clearance conditions.

Aerodynamic Assessment Cases are assessed in a standardized manner, with all engineering assessment indicators (Aerodynamic Loading Level, Ground-Clearance Influence, Wake Interaction Strength, Shielding Behaviour, Comparative Performance Rating) evaluated in the same sequence. Therefore, the differences found between the investigated configurations are not due to the way the evaluation was done but are due to their inherent aerodynamic properties.

The use of these complementary engineering views allows for the extension of the interpretation of published aerodynamic measurements beyond the standard parameter-by-parameter approach as illustrated by UGCAF. The framework provides consistent relationships between aerodynamic loading, ground-clearance effects, wake interaction and shielding, allowing a systematic and reproducible comparison of different tandem plate configurations in a single analytical framework.

One of the strengths of UGCAF is that it is independent of particular types of experimental or numerical technique. The framework is based on published aerodynamic data from either experimental or numerical studies and maintains the integrity of the original data sets, but also interprets the data in an engineering-oriented way. Therefore, with availability of the aerodynamic variables (drag coefficient, pressure coefficient, ground-clearance ratio, and geometry) required for the aerodynamic study of alternate tandem configurations, UGCAF can be readily applied to future aerodynamic studies.

The unification of the engineering interpretation suggested by UGCAF offers a methodological link that connects the framework implementation presented in this section with quantitative evaluation presented in the next section. For this reason, the engineering observations obtained through the proposed framework are used as a basis for the detailed results and discussion that follows, to systematically discuss the effect of ground clearance on aerodynamic loading, wake interaction, shielding behaviour, and overall aerodynamic performance.

5. RESULTS AND DISCUSSION

5.1 Aerodynamic Loading Assessment

Aerodynamic loading is the first engineering indicator to be assessed in a proposed Unified Ground Clearance Assessment Framework (UGCAF). The published drag measurements are systematically interpreted based on the cases for aerodynamic assessment in section 4 with the objective of determining the distribution of aerodynamic loading along the tandem configuration. Instead of analysing drag coefficients one after the other, UGCAF combines the published data into a comprehensive engineering evaluation which enables an objective comparison of the investigated configurations(See Table VII).

TABLE VII. UGCAF ENGINEERING ASSESSMENT OF AERODYNAMIC LOADING

Aerodynamic Feature	**Published Aerodynamic Observation**	**UGCAF Assessment**	**Engineering Interpretation**
Leading plate	Highest drag coefficient throughout the investigated configurations	Critical aerodynamic loading region	Aerodynamic loading is dominated by direct stagnation of the approaching flow.
Second plate	Largest reduction in drag coefficient	Strong wake shielding	Upstream wake substantially suppresses aerodynamic loading on the downstream plate.
Third plate	Partial recovery of aerodynamic loading	Moderate wake redevelopment	Progressive restoration of airflow increases aerodynamic loading.
Fourth plate	Continued loading recovery	Weak shielding effect	Wake recovery becomes dominant and aerodynamic loading approaches stabilized conditions.
Ground-clearance response	Downstream plates exhibit greater loading variation than the leading plate	Position-dependent sensitivity	Ground clearance primarily influences wake redevelopment rather than the leading plate itself.
Overall tandem configuration	Non-uniform aerodynamic loading distribution	Integrated aerodynamic response	Aerodynamic loading results from the coupled interaction among wake evolution, plate position, and ground effect.

The UGCAF assessment shows that the loading on the tandem configuration is not uniform. The first plate is subjected to the highest aerodynamic loading due to direct exposure to the incoming flow and the second plate to the largest reduction as a result of wake shielding. The progressive restoration of the wake leads to progressive recovery of aerodynamic loading on the third and fourth plates as the air flow redevelops downstream.

The leading plate is relatively unaffected by clearance changes, whereas the downstream plates are very sensitive to clearance changes. This behaviour illustrates that aerodynamic loading is not only a function of the position of the plate, but is also dependent on the plate's proximity and wake redevelopment.
UGCAF offers a combined engineering interpretation that relates aerodynamic loading to the flow mechanisms unlike conventional analyses based on drag coefficients alone. The framework focuses on the process of wake redevelopment as the most important process that affects down-stream load recovery and provides a consistent framework for assessing aerodynamic behaviour for various ground-effects. This assessment is necessary to begin the analysis of the influence of ground clearance.

5.2 Ground-Clearance Influence Assessment

The second engineering indicator that is analyzed in the proposed Unified Ground Clearance Assessment Framework (UGCAF) is ground clearance. The framework evaluates changes in the aerodynamics loading and wake throughout the tandem configuration during the selected investigation, using the selected investigation. The concept of ground clearance is not treated as a stand-alone geometric parameter, but rather how it affects the aerodynamic behaviour of the system as a whole is assessed by UGCAF. The engineering assessment summary is summarized in Table VIII.

TABLE VIII. UGCAF ENGINEERING ASSESSMENT OF GROUND-CLEARANCE INFLUENCE

Assessment Aspect	Published Aerodynamic Observation	UGCAF Assessment	Engineering Interpretation
Low ground clearance	Reduced downstream aerodynamic loading	Strong ground-effect influence	Restricted underbody flow suppresses wake recovery.
High ground clearance	Increased downstream aerodynamic loading	Reduced ground-effect influence	Improved airflow promotes wake redevelopment.
Leading plate	Small variation in aerodynamic loading	Low sensitivity	Direct exposure dominates aerodynamic loading.
Downstream plates	Greater loading variation	High sensitivity	Wake evolution is strongly influenced by ground clearance.
Overall configuration	Position-dependent aerodynamic response	Integrated ground-clearance effect	Ground clearance governs wake development rather than uniformly affecting all plates.

From the UGCAF assessment, it is seen that the effect of ground clearance is substantially different for different tandem configurations. However, the aerodynamic loading of the plates downstream changes more with increasing ground clearance, while the plate upstream changes less with ground clearance. This behavior is indicative of the aerodynamic effect of the ground clearance being linked to the wake redevelopment, not to the modification of the incoming flow.
The engineering point of view, increasing the clearance between tandem will increase the flow passage below the tandem, which will increase the recovery of the wake before it hits downstream plates. This means that the aerodynamic loading slowly builds up and the shielding effect slowly decreases. The results show that ground clearance can be treated as a flow-control parameter on the system level and is an important parameter for controlling the aerodynamic performance under ground-effect conditions.

5.3 Wake Interaction Assessment

The third engineering indicator being evaluated according to the proposed Unified Ground Clearance Assessment Framework (UGCAF) is wake interaction. UGCAF evaluates the role of wake redevelopment under various ground clearance conditions and the aerodynamic loading on downstream plates due to the wake generated by the upstream plates, based on the selected investigation. The results of the engineering assessment are summarized in Table IX.

TABLE IX. UGCAF ENGINEERING ASSESSMENT OF WAKE INTERACTION

Assessment Aspect	Published Aerodynamic Observation	UGCAF Assessment	Engineering Interpretation
Wake behind the leading plate	Significant reduction in downstream loading	Strong wake interaction	Upstream wake substantially modifies the incoming flow.
Downstream wake recovery	Progressive increase in aerodynamic loading	Moderate wake redevelopment	Flow velocity gradually recovers downstream.
Ground-clearance influence	Higher clearance increases loading recovery	Reduced wake intensity	Improved underbody flow accelerates wake redevelopment.
Plate-position dependency	Wake effects vary among successive plates	Position-dependent interaction	Each plate experiences a different aerodynamic environment.
Overall configuration	Continuous wake evolution	Integrated wake behaviour	Wake interaction governs aerodynamic force redistribution.

Redistribution of aerodynamic loading in the tandem configuration is primarily affected by wake interaction. Aerodynamic loading is appreciably lower in the wake behind the leading plate, so the strongest wake effect is found in this area. The flow is gradually redeveloping the wake which increases the aerodynamic loading on subsequent plates.
Ground clearance is also shown to be a very critical parameter for wake interaction in the assessment. A higher clearance ratio aids in more rapid wake recovery, decreases wake intensity and increases the aerodynamic loading on downstream

plates. The results illustrate the wake interaction as an evolving phenomenon, which is a system-level property and is dependent on the position of the plates and their ground effect conditions.

5.4 Shielding Behaviour Assessment

The fourth engineering indicator assessed in the proposed Unified Ground Clearance Assessment Framework (UGCAF) is shielding behaviour. With the chosen investigation, UGCAF determines how much aerodynamic loading is reduced on the downstream plates by the upstream plates, and how this is affected by the position of the plates and the ground clearance. The engineering assessment results are summarized in Table X.

TABLE X. UGCAF ENGINEERING ASSESSMENT OF SHIELDING BEHAVIOUR

Assessment Aspect	Published Aerodynamic Observation	UGCAF Assessment	Engineering Interpretation
Leading plate shielding	Maximum protection provided to the second plate	Strong shielding effect	The upstream plate effectively blocks the incoming airflow.
Downstream shielding	Shielding gradually decreases along the tandem arrangement	Progressive shielding reduction	Wake recovery increases downstream aerodynamic exposure.
Ground-clearance influence	Higher clearance weakens shielding	Reduced shielding effectiveness	Improved airflow beneath the plates accelerates wake redevelopment.
Plate-position dependency	Shielding varies among successive plates	Position-dependent shielding	The shielding effect depends on the relative location of each plate.
Overall configuration	Non-uniform shielding distribution	Integrated shielding behaviour	Shielding plays a major role in aerodynamic force redistribution.

Shielding behaviour is strongest immediately behind the leading plate as the stream of aerodynamic loading is greatly diminished in the wake of the upstream plate. The downsteam development of the flow causes a progressive loss of shielding due to wake recovery, so that subsequent plates receive a greater aerodynamic loading.

The assessment also indicates that higher ground clearances might result in lower shielding effectiveness, due to improved flow recovery under the tandem configuration. Hence, the extent of the shielding behaviour is not only related to the geometric arrangement, but also to the wake development, the position of the plates and the ground-effect conditions. This is to validate that protection is one of the important mechanisms controlling the aerodynamic response of the tandem plate system.

5.5 Comparative Performance Assessment

The four engineering indicators: Aerodynamic Loading, Ground-Clearance Influence, Wake Interaction and Shielding Behaviour are combined to a unified comparative assessment in the final stage of the proposed Unified Ground Clearance Assessment Framework (UGCAF). This integrated evaluation is an engineering interpretation of the aerodynamic performance of the tandem configuration as a whole, instead of relying on individual aerodynamic observations. Table 11 presents the final comparative assessment.

TABLE XI. FINAL UGCAF COMPARATIVE PERFORMANCE ASSESSMENT

Engineering Indicator	Assessment Outcome	Engineering Contribution
Aerodynamic Loading	Critical loading identified on the leading plate	Defines overall force distribution.
Ground-Clearance Influence	High sensitivity for downstream plates	Regulates wake redevelopment and loading recovery.
Wake Interaction	Strong interaction between successive plates	Controls aerodynamic force redistribution.
Shielding Behaviour	Maximum shielding behind the leading plate	Reduces downstream aerodynamic loading.
Overall UGCAF Assessment	Integrated aerodynamic behaviour successfully characterized	Provides a unified engineering interpretation of the tandem configuration.

The tandem configuration's aerodynamic performance is found to be dependent on the aerodynamic loading, ground-clearance effects, wake development, and shielding behaviour of the configuration. Each indicator will tell a different aspect of the flow field, but together, they will give a general engineering understanding of the aerodynamic system.

UGCAF integrates several engineering indicators in a common framework, as opposed to conventional analyses that assess each indicator independently. The proposed framework is practically applied in engineering design, and a unified interpretation leads to better aerodynamic evaluation consistency and aids in objective comparison under various ground-effect conditions for tandem configurations.

5.6 Overall Discussion and Engineering Implications

The outcomes of the study indicate that the proposed Unified Ground Clearance Assessment Framework (UGCAF) is systematic in explaining selected investigation in an engineering context. Instead of analyzing aerodynamics parameters separately, the analysis framework incorporates aerodynamic loading, ground-clearance influence, wake interaction and shielding behaviour together, providing a comprehensive understanding of the aerodynamics response of tandem tilted flat-plate configuration.

UGCAF provides a standardized analytical procedure to assess relationships between several aerodynamic mechanisms which is more comprehensive than traditional techniques that report drag coefficients and that describe individual

aerodynamic phenomena. This comprehensive interpretation makes engineering assessments more consistent and allows to compare different aerodynamic configurations based on a common evaluation system.
The major asset of UGCAF is its analytical framework which is transferable. The framework relies on published aerodynamic data sets, not a particular experimental or computational technique, and can thus be easily applied to other aerodynamic bluff-body configurations, ground-effect studies, and comparative aerodynamic studies, where multiple performance indicators need to be interpreted simultaneously. This flexibility allows for an extension of the usefulness of available aerodynamic datasets, without any need for further experiments or numerical simulations.
However, the present one has its drawbacks. The current assessment was made with just one published tandem flat-plate dataset and engineering interpretation remains reliant on the quality and completeness of the available aerodynamic observations. UGCAF also does not present an aerodynamic model for prediction, but offers an analytical assessment methodology for use in conjunction with experimental measurements and/or computational fluid dynamics analyses.
The UGCAF could be extended for future research to other aerodynamic geometries, vehicle configurations, and ground-effect conditions. The further development of the proposed framework with adding of other aerodynamic performance indicators and validation with other published data sets would further increase the generality and engineering applicability of the proposed framework.

6. CONCLUSIONS

This study presented a transferable analytical methodological framework for systematic interpretation of published aerodynamic datasets of tandem tilted flat plates under ground-effect conditions, which is the Unified Ground Clearance Assessment Framework (UGCAF). UGCAF is different from the traditional aerodynamic studies which report drag coefficient, pressure distributions and wake characteristics as standalone performance measures, and instead combines five complementary engineering parameters – Aerodynamic Loading, Ground-Clearance Influence, Wake Interaction Strength, Shielding Behaviour and Comparative Performance Rating – into one single engineering assessment methodology. The framework was worked out for the demonstration of its practical application and analytical capability with a representative published experimental dataset. The assessment identified that the aerodynamic loading depends on the interplay of plate position, wake evolution and ground-effect conditions and is not exclusively dependent on the geometric parameters. In addition, the combined interpretation showed that the greater the ground clearance, the more successful wake redevelopment is, the less the aerodynamic shielding, and the greater the aerodynamic loading recovery on the downstream plates, while the loading on the leading plate is largely due to direct stagnation loading. The main scientific achievement of this work is not the production of new experimental measurements or computational fluid dynamics (CFD) simulations, but the production of a methodological framework which can be standardised and used systematically to reorganise, assess and interpret validated selected investigation. UGCAF bridges the gap between conventional aerodynamic parameters and connected engineering parameters to give a more in-depth engineering interpretation of aerodynamic behaviour. The proposed framework is not tied to the specific data acquisition method and can thus be utilized with validated experimental measurements, CFD simulations, and other trustworthy aerodynamic data sets. This flexibility allows for comparability of the engineering analyses of the different aerodynamic investigations without compromising the integrity of the physical data of the original published observations. The present study has established the applicability of UGCAF for the studied case, but the generality and robustness of the UGCAF approach are enhanced by employing it on a representative set of published aerodynamic datasets, different representative geometric configurations, and unsteady flow conditions. Overall, UGCAF gives a practical, reproducible and transferable methodology that together with experimental and computational studies will serve as a unified engineering approach for systematic interpretation of available aerodynamic data and for more standardised aerodynamic assessment in future research.

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